ADA085490

LEVEL III

AWS/TR-80/001

FORECASTERS' GUIDE ON AIRCRAFT ICING

March 1980

Approved For Public Release; Distribution Unlimited

AIR WEATHER SERVICE (MAC)
Scott AFB, Illinois 62225

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REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. ~~REPORT NUMBER~~ 14 AWS/TR-80/001	2. GOVT ACCESSION NO. AD-A085490	3. RECIPIENT'S CATALOG NUMBER
4. ~~TITLE~~ (and Subtitle) 6 FORECASTERS' GUIDE ON AIRCRAFT ICING.		5. TYPE OF REPORT & PERIOD COVERED 9 Technical Report,
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s)		8. CONTRACT OR GRANT NUMBER(s) 12 61
9. PERFORMING ORGANIZATION NAME AND ADDRESS Air Weather Service Scott AFB, Illinois 62225		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS Air Weather Service Scott AFB, Illinois 62225	11	12. REPORT DATE March 1980
		13. NUMBER OF PAGES 58
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

This report supersedes and replaces AWSM 105-39, Forecasters' Guide on Aircraft Icing, 7 January 1969. The AWSM 105-39 and its changes 1-3 dated 10 November 1969, 15 October 1971, and 11 January 1974, respectively, have been included.

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Meteorology
Forecasting
Aircraft Icing

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report presents information on aircraft icing that forecasters can use in forecasting and briefing for aircraft operations. It covers the atmospheric conditions that are favorable for aircraft icing and also how different aircraft types affect the potential for icing.

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

PREFACE

This AWS Technical Report is a republication of AWSM 105-39, 7 January 1969. The changes 1-3 to AWSM 105-39 have been incorporated. Additional changes and corrections have been included prior to publication.

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Chapter 1

INTRODUCTION

1. General:

a. Aircraft icing is one of the major weather hazards to aviation. Ice on the airframe decreases lift and increases weight, drag, and stalling speed. In addition, the accumulation of ice on exterior movable surfaces affects the control of the aircraft. In the past, airframe icing was a hazard mainly because it tended to cause difficulty in maintaining altitude. Today, although most aircraft have sufficient reserve power to fly with a heavy load of ice, airframe icing is still a serious problem because it results in greatly increased fuel consumption and decreased range. Further, the possibility always exists that engine-system icing may result in loss of power.

b. Two basic conditions must be met for ice to form on an airframe in significant amounts. (The problems of engine icing are discussed in chapter 3.) First, the aircraft-surface temperature must be colder than 0°C. Second, supercooled water droplets; i.e., liquid-water droplets at subfreezing temperatures, must be present. Water droplets in the free air, unlike bulk water, do not freeze at 0°C. Instead, their freezing temperature varies from an upper limit near - 10°C to a lower limit near -40°C. The smaller and purer the droplets, the lower is their freezing point. When a supercooled droplet strikes an object such as the surface of an aircraft, the impact destroys the internal stability of the droplet and raises its freezing temperature. Therefore, the possibility of icing must be anticipated in any flight through supercooled clouds or liquid precipitation at temperatures below freezing. In addition, frost sometimes forms on an aircraft in clear humid air if both aircraft and air are at subfreezing temperatures.

c. Accurate forecasts of the occurrence and type of precipitation, and of the type, location, altitude, thickness, amount, and temperature of clouds must be available before completely accurate aircraft-icing forecasts can be made. *The discussions in this report with regard to the forecasting of aircraft icing are based on the assumption that cloud, temperature, and precipitation forecasts have already been made.*

d.

The aids and procedure suggested are subject to trial and experience. It is not to be expected that all forecasters can improve their icing forecasts with them, as various other valid ways of approaching the forecast have been worked out (if only subjectively) in the long experience of individual forecasters. The procedure presented aims to exploit the results of research much of which is neither readily accessible nor known to most forecasters. Comments on experience with these data and suggested changes to this report will be sent to AWS/DNT.

2. Types of Icing. There are three basic forms of ice accumulation on aircraft: rime ice, clear ice, and frost. In addition, mixtures of rime and clear ice are common.

a. **Rime ice** is a rough, milky, opaque ice formed by the instantaneous freezing of small supercooled droplets as they strike the aircraft. The fact that the droplets maintain their nearly spherical shape upon freezing and thus trap air between them gives the ice its opaque appearance and makes it porous and brittle.

b. **Clear ice** is a glossy, clear or translucent ice formed by the relatively slow freezing of large supercooled droplets. The large droplets spread out over the airfoil before complete freezing, forming a sheet of clear ice.

c. **Frost** is a light, feathery deposit of ice crystals which usually forms on the upper surfaces of parked aircraft by radiational cooling in a manner similar to the formation of hoarfrost on the ground. Frost may also form on aircraft in flight during descent from subfreezing air into a warmer, moist layer below, but this is considered rare and harmless. Since the formation of frost on parked aircraft and other terrestrial objects is a purely local-forecasting problem, it is not included in this manual. Jacobs [20] and Thompson [45] have proposed methods of attacking this problem.

3. Intensities of Icing:

a. **Intensity Forecasts.** Forecasts of icing intensity should represent the probable maximum intensity based upon meteorological criteria expected to exist at a point in space and time for which the forecast is made, and not necessarily the intensity which the aircraft will encounter. This is because the variations in flight paths actually flown, aircraft types, and pilot procedures and techniques are non-meteorological factors which influence the actual ice accumulation of a particular aircraft under a given set of meteorological conditions. The individual pilot must determine the effect

which a forecast icing intensity will have on his particular aircraft based on his knowledge of his aircraft and other non-meteorological operational considerations.

★ b. Intensity Standards. The standards for reporting icing are based on a recommendation set forth by the subcommittee for the Aviation Meteorological Services in the Office of the Federal Coordinator for Meteorology in Nov 1968.

(1) Trace of icing. Icing becomes perceptible. Rate of accumulation slightly greater than rate of sublimation. It is not hazardous even though deicing/anti-icing equipment is not utilized, unless encountered for an extended period of time—over one hour.

(2) Light icing. The rate of accumulation may create a problem if flight is prolonged in this environment (over one hour). Occasional use of deicing/anti-icing equipment removes/prevents accumulation. It does not present a problem if the deicing/anti-icing equipment is used.

(3) Moderate icing. The rate of accumulation is such that even short encounters become potentially hazardous and use of deicing/anti-icing equipment or diversion is necessary.

(4) Severe icing. The rate of accumulation is such that deicing/anti-icing equipment fails to reduce or control the hazard. Immediate diversion is necessary.

Paragraph 29 and table 4 show the relationship of icing intensity to basic meteorological parameters. Convention has been to designate icing intensity in terms of its operational effect upon the reciprocating engine, straight wing transport aircraft, as C-54, C-118. The pilot should, after receiving the icing intensity forecast, refer to the aircraft dash one for recommended actions. If necessary, AWS personnel should emphasize to the pilot that the icing intensities were verified against straight wing reciprocating transport aircraft. The pilot should refer to the aircraft dash one for specific instructions when flying in icing areas prescribed by the forecast. AWS personnel, in turn, must be familiar with effects of icing on a particular aircraft in order to properly assess pilot reports of icing conditions.

c. **International Differences.** Although all concerned US Federal agencies have now agreed to these standard definitions of icing intensities, international standardization has not yet been accomplished. Some other countries use completely different terms to describe the various intensities and types of icing and give no indication of the standard aircraft type to which their icing intensities refer. The World Meteorological Organization (WMO) uses 10 code figures in the TAF for icing but does not explain the meaning of the intensities and does not refer to any standard aircraft type. (See AWSM 105-24 for WMO TAF Code and relationship of the WMO code figures to the intensities given in table 4).

4. **De-Icing and Anti-Icing Methods.** In the past, most military aircraft, exclusive of training aircraft, were equipped with de-icing

equipment. Many of the newer models, particularly the high-altitude jet aircraft which operate mostly at levels where icing is rare, are not so equipped. Although various waxes, paints, lacquers, and lubricants have been tried for de-icing or anti-icing purposes, there are still only three methods commonly used for preventing or eliminating airframe icing on service aircraft.

a. **Mechanical Boots.** The leading edges of wing and tail surfaces are equipped with rubber skins which normally assume the contour of the airfoil. During icing situations, compressed air is cycled through ducts, causing a mechanical deformation of the boots. The stress produced by the pulsating boots causes the ice to fracture, and the air stream peels the resulting ice fragments from the boots. Mechanical de-icing techniques are used only after ice has begun to form.

b. **Anti-Icing Fluids.** Anti-icing fluids are used on rotating surfaces, such as propellers, where the centrifugal force produced by the rotation spreads the fluid evenly over the entire surface. These fluids are effective because they prevent ice, as it forms, from adhering to the coated surface; thus, the ever-present centrifugal force can throw it off. Anti-icing fluids are most effective when applied before the icing starts.

c. **Heat.** The application of heat to a potential or actual icing surface to raise its temperature above freezing is the most obvious method of ice prevention and dissipation. This is the system used mostly on those modern aircraft which are equipped with de-icing equipment. The leading edges of the wing and tail surfaces are heated by hot air or electrical means. On reciprocating-engine aircraft, hot air from a manifold around the engine can be piped to those areas which are usually the site of the most serious icing. On turbojet aircraft, hot air can be piped from the compressor. Either type of heating may be continuous or cyclic. In the past, practical considerations of weight, heat exchange, and temperature effects on structure and electrical insulation limited the effectiveness of a continuously-heated ("hot-wing") system, and resulted in preference for the cyclic hot-air de-icing system. In addition, this method is the most economical system with respect to weight. Recent equipment developments have partially overcome these limitations. Although cyclic heating or continuous heating may be used to remove ice already formed, continuous heating is now usually used for ice prevention.

5. Icing Hazards on or Near the Ground. Certain icing hazards on or near the ground are mentioned here although they are outside the scope of this report. They are the concern of operations personnel, but their existence should be mentioned in the weather briefing.

a. One hazard results when wet snow is falling during takeoff. This situation can exist when the free-air temperature at the ground is near 0°C. The wet snow sticks tenaciously to aircraft components, particularly the wings, and freezes when the aircraft encounters markedly colder temperatures during its climb. This hazard is similar to that resulting from run-back icing in that snow collects on the upper airfoil surfaces (see paragraph 32).

b. If not removed before takeoff, frost, sleet, frozen rain, and snow accumulated on parked aircraft are operational hazards. It is common practice to place aircraft in a hanger until the accumulation has melted, or to clean the airfoil surfaces by some other means before a flight is attempted.

c. Another hazard, which is not so-well publicized or recognized, arises from the presence of puddles of water, slush, or mud on airfields. When the air temperature and the airframe temperature are colder than 0°C, water blown by the propellers or splashed by wheels can form ice on control surfaces and windows. Freezing mud is particularly dangerous because the dirt may clog controls and cloud the windshield. Mud, slush, or water which freezes in the wheel wells and on wing-flap hinges may prevent the retraction of wheels or flaps, or, more seriously, cause them to freeze in a retracted or semi-retracted position.

Chapter 2

PHYSICAL FACTORS AFFECTING AIRCRAFT ICING

6. General. As stated in chapter 1, significant airframe icing occurs only in clouds or precipitation composed of supercooled water droplets. The amount and rate of icing depend on a number of meteorological and aerodynamic factors, including temperature, the amount of liquid water in the path of the aircraft, the fraction of this liquid water collected by the aircraft (the collection efficiency), and the amount of aerodynamic heating. Collection efficiency, in turn, is affected by the size of the aircraft component involved, airspeed, and droplet size. Air frame and engine-system icing problems peculiar to the various types of aircraft are discussed in chapter 3.

7. Temperature. Temperature has a direct effect on the fraction of water which freezes instantaneously on impact. When a large droplet strikes an aircraft with airframe-surface temperatures barely below freezing, only a fraction of the droplet may freeze, the remainder being carried off by the airstream. In the case of smaller droplets, or large droplets at a slightly lower temperature, the entire droplet may freeze onto the aircraft. The relationship of temperature to liquid-water content is described in the next paragraph.

8. Liquid-Water Content. Under icing conditions, the liquid-water content in the cloud is probably the most important parameter in determining the ice-accumulation rate. In general, the lower and warmer the base of the cloud, the higher is its water content. Within the cloud, the average liquid-water content increases with altitude to a maximum value and then decreases. The maximum concentration usually occurs at a lower level in stratiform than in cumuliform clouds, and the average liquid-water content of a stratiform cloud is usually less than that of a cumuliform cloud. Graphs which give an intensity estimate of rime and clear icing, based upon the liquid-water content of stratiform and cumuliform clouds, respectively, as a function of flight altitude and cloud-base (LCL) temperature, are in chapter 5.

9. Droplet Size:

a. As shown in the next paragraph, droplet size affects the collection efficiency and hence the icing rate. The size-distribution and median size of the droplets in a cloud are related to the type, depth, and age of the cloud, to the strength of the updrafts, to the humidity of the air mass, and to other factors. Since both the liquid-water content and droplet size are generally greater in cumuliform clouds than other cloud types, it would appear at first glance that cumuliform clouds should be particularly conductive to icing. However, the effect exerted by other variables, such as the speed, shape, and size of the aircraft components, may be sufficiently great for meteorological conditions leading to trace icing for one type of aircraft to result in light or moderate icing for another.

b. Droplet size is difficult to estimate from aircraft in flight. NACCAM has defined droplet category and size in terms of ice-formation locations. (Table 1a).

10. Collection Efficiency. The icing rate depends to a large degree upon the collection efficiency of the aircraft component involved. Collection efficiency, the fraction of the liquid water collected by the aircraft, varies directly with droplet size and aircraft speed, and inversely with the size or geometry of the collecting surface. The size of an aircraft component is described in terms of the radius of curvature of its leading edge (see figure 1). Those components which have large radii of curvature (canopies, thick wings, etc.) collect but a small percentage of the cloud droplets, especially of the smallest droplets.

Components having small radii of curvature (antenna masts, thin wings, etc.) deform the airflow less, permitting a higher proportion of droplets of all sizes to be caught. Once ice begins to form, the shape of the collecting surface is modified, with the radius of curvature nearly always becoming smaller and the collection efficiency increasing. In general, fighter-type aircraft, because of their greater speed and thinner wings, have higher collection efficiencies than do cargo aircraft. The effect of droplet size on collection efficiency, computed for a radius of curvature (cylindrical) of 15 cm and a true airspeed of 175 knots, is shown in table 1b.

TABLE 1a

Cloud-Droplet-Size Scale.

Category	Droplet Diameter	Observational Criteria
Small	<10 Microns	Ice formations limited to leading edge radius of large components.
Medium	10-30 Microns	Ice formations occur aft of leading edge radius but do not extend aft of normally protected surfaces.
Large	30-100 Microns	Ice formations extend aft of normally protected surfaces.
Freezing Rain or Drizzle	100-1000 Microns	Ice formations extend aft to point of maximum component projection into the air stream.

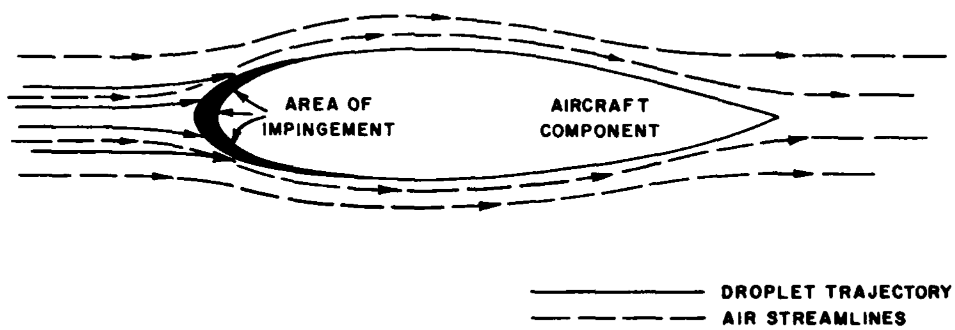


Figure 1—Area of Impingement on an Aircraft Component in an Airstream.

11. Aerodynamic Heating. This is the temperature rise resulting from adiabatic compression and friction as the aircraft penetrates the air. (The saturation-adiabatic laws, including the effects of fusion and evaporation, apply to flight through clouds.) The amount of heating varies primarily with the speed of the aircraft and the altitude (actually, air density), and may range from approximately one degree for very slow aircraft at low altitudes to more than 50 degrees for supersonic jets at low altitudes. Thus, although it is frequently stated that an aircraft flying through any supercooled liquid-

TABLE 1b

Collection Efficiency vs. Droplet Size (data after Jones[22], based on radius of curvature of 15 cm and true airspeed 175 kt).

Droplet Diameter (microns)*	Collection Efficiency
20	0.1 - 0.2
40	0.4
60	0.6

* 1 micron = 0.001 millimeter

water cloud must anticipate icing, it actually is necessary that the amount of supercooling exceed the amount of aerodynamic heating. Graphs of the aerodynamic temperature rise for various airspeeds and altitudes are given in chapter 5.

Chapter 3

OPERATIONAL ASPECTS OF AIRCRAFT ICING

12. General. There is probably a greater range of aircraft models and characteristics in the Air Force inventory today than ever before. This range may become still greater in the future, because new aircraft are being developed faster than old ones are becoming obsolete. Therefore, the discussion in this manual will be limited to the operational aspects of icing for the general types of aircraft, rather than for specific models. Overall, icing is a contributing factor in only a small fraction of USAF aircraft accidents and incidents. The proportion of all accidents due in any way to icing has decreased considerably over the last 20 years, through better design and operating practices and the greater use of jets. Refer to the flight manual on an aircraft for information on the icing problems peculiar to that model or class.

13. Reciprocating Engine Aircraft. Because of their relatively low speed and service ceilings, reciprocating engine aircraft, long referred to as "conventional" aircraft, often operate for long distances (times) in more-or-less continuous icing conditions. During the period 1946-1958, the larger part (77%) of USAF accidents in which icing was a factor involved reciprocating engine aircraft. During 1959-1965, the reciprocating engine aircraft accounted for less than a third (32%) of all USAF accidents and incidents with icing as a factor, reflecting the decreasing proportion of such aircraft in the inventory. About 90% of these cases were airframe (structural) icing, the rest engine-induction[17]:

a. The relatively thick wings, canopies, etc., which are characteristic of this group of aircraft, have a smaller collection efficiency than those of the trimmer and faster turbojet aircraft. However, the actual hazard of icing for conventional aircraft tends to be greater than for jets because the slower speeds produce less aerodynamic heating the conventional aircraft are generally subjected to icing conditions over longer time periods, and, most important, because they operate at altitudes more conducive to icing.

b. Propeller icing varies along the blade since the differential velocity along the blade results in a temperature increase (due to aerodynamic heating) from the hub toward the propeller tip[39]. Ice has frequently been observed to form near the hub of the aircraft propellers on ordinary transport aircraft at an ambient air temperature between 0°C and -5°C and to increase gradually as the aircraft flies through colder air, reaching the blade tips at a temperature near -15°C.

c. Reciprocating engines experience impact icing on air scoops, scoop inlets (ducts), carburetor inlet screens, and other protuberances of the induction system[26].

d. Carburetor icing may occur with free-air temperatures well above freezing when fuel is mixed with air having the proper temperature-moisture conditions. The cooling effect is due to the reduction of pressure by a venturi effect in the carburetor and to evaporation of the fuel. Usually the total cooling effect is less than 20°C, but values as high as 40°C have been achieved experimentally [14]. Pilot-controlled heating systems can provide complete protection from carburetor icing.

14. Turbojet Aircraft. These high-speed aircraft generally cruise at altitudes well above levels where moderate icing exists. Icing encountered above 30,000 feet or below -35°C is considered very rare[3]. While during the period 1946-1958, 22% of USAF aircraft accidents with an icing factor involved turbojet aircraft, about 65% involved turbojets during 1959-1965. Of the latter, 62% were airframe and the remainder induction icing.

a. High-speed aircraft have their greatest problem with icing during takeoff, climb, approach, or go-around [28][34], primarily because of the greater probability of encountering supercooled clouds at low altitudes. Also, the reduced speed during these maneuvers results in a decrease in the aerodynamic heating, and hence an increase in ice-accumulation potential.

b. Turbojet engines experience icing both externally and internally. All exposed surfaces which are subject to direct impingement of water droplets may collect ice, and the inlet ducting and internal elements are also subject to icing [18]. Similar to the carburetor icing of reciprocating-engine aircraft, icing can occur in the inlet duct of a turbojet at temperatures well above freezing, when the aircraft is operating on the ground or at very low speeds. The greatest icing hazard, and the one most difficult to protect against, involves the compressor inlet screen [47]. The thrust produced by a turbojet engine is a function of the mass airflow through the engine. Icing on the engine components reduces this airflow, thus favoring compressor pressure losses, reduced thrust, and increased fuel consumption.

c. Some comparison of the icing hazard is possible between the fighter and transport and between the bomber and transport which are jet-powered. Because of the greater aerodynamic heating due to its greater speed, the jet fighter may pick up less ice than the jet transport under the same meteorological conditions. Also, at similar rates of ice accretion, the airfoil drag due to the presence of ice increases more on transport than on fighter planes. The fighter's rate of climb is thereby less affected than that of the transport [48]. Under similar meteorological and operational conditions, the jet bomber also collects less ice than the jet transport. There is less impingement on the upper surface of the bomber's wings than on the transport's, while impingement on the lower surface is about the same [11].

15. Turbo-Propeller Aircraft. The problems of aircraft icing for turbo-propeller aircraft combine those associated with conventional aircraft and turbojet aircraft [1]. Collection efficiencies of turbo-propeller aircraft are generally higher than for conventional aircraft, but this factor is partially offset by the increased aerodynamic heating at the higher airspeeds of turbo-propeller aircraft. Engine-icing problems are similar to those encountered by turbojet engines, while propeller icing can also occur.

16. Rotary-Wing Aircraft. During the period of 1946 through 1965, only a few USAF helicopter accidents involving icing were reported; these involved the induction system [17]. The statistics are misleading since rotary-wing aircraft seldom operated under IFR conditions (clouds):

a. The problems of icing on rotary-wing aircraft are related to those involving wings and propellers [32]. Rotor-icing is slightly different from propeller-icing because of the lower rotation speed of the rotors. Ice accretion on rotor-blades also differs from that on fixed wings of conventional aircraft, due to the smaller scale of the helicopter wing, to the variation of airspeed with rotor-blade span, the cyclic pitch-changing of the blades, and the cyclic variation of airspeed at any given point on the blade in conditions of forward flight [25]. Ice accretion on the main rotor blades is more hazardous than ice on fixed-wing aircraft because the helicopter, while hovering, normally operates very near its peak operational limits [19]. Tests conducted by the Canadian National Aeronautical Establishment indicate that small amounts of ice accretion (about 3/16" thick) are more than sufficient to prevent a helicopter from maintaining height during hovering flight [42]. Secondary effects are vibration, damage by flying ice, and limitation of throttle movement by premature stoppage.

b. Icing also affects the tail rotor, control rods and links, and air intakes and filters. Other parts of the helicopter are comparatively poor collectors because of their relatively large scale and low airspeed.

Chapter 4

DISTRIBUTION OF ICING IN THE ATMOSPHERE

17. General. The atmospheric distribution of potential aircraft icing zones is mainly a function of temperature and cloud structure. These factors, in turn, vary with altitude, synoptic situation, orography, location, and season.

18. Altitude and Temperature:

a. It is widely accepted that aircraft icing is limited to the layer of the atmosphere lying between the freezing level and the -40°C isotherm. Icing has occasionally been reported at temperatures colder than -40°C in the upper parts of cumulonimbus and other clouds. In general, the frequency of icing decreases rapidly with decreasing temperature, becoming rather rare at temperatures below -30°C (see chapter 5 for graphs of the relationship between icing frequency and temperature). The normal vertical temperature distribution in the atmosphere is such that icing is usually restricted to the lower 30,000 feet of the troposphere.

b. The type of icing, also, is highly dependent on temperature. Clear ice usually occurs at temperatures just below freezing, whereas rime ice predominates at lower temperatures. According to AWS reconnaissance reports (at 500 mb and 700 mb)[37], the relative frequency of icing by types is as follows: clear, 10%; clear-rime mixture, 17%; rime, 72%; and frost (in flight), 1%.

19. Clouds. Aircraft icing can occur in stratiform or cumuliform clouds:

a. **Stratiform.** Icing in middle-and low-level stratiform clouds is confined, on the average, to a layer between 3,000 and 4,000 feet thick. The intensity of the icing generally ranges from a trace to light, with the maximum values occurring in the upper portions of the cloud. Both rime and mixed icing are observed in stratiform clouds. The main hazard lies in the great horizontal extent of some of these cloud decks. High-level stratiform clouds are composed mostly of ice crystals and give little icing.

b. **Cumuliform.** The zone of probable icing in cumuliform clouds is smaller horizontally but greater vertically than in stratiform clouds. Further, icing is more variable in cumuliform clouds because many of the factors conducive to icing depend to a large degree on the stage of development of the particular cloud. Icing intensities may range from generally a trace in small supercooled cumulus to often light or moderate in cumulus congestus and cumulonimbus. The most severe icing occurs in cumulus congestus clouds just prior to their change to cumulonimbus. Although icing occurs at all levels above the freezing level in a building cumulus, it is most intense in the upper half of the cloud. Icing is generally restricted to the updraft regions in a mature cumulonimbus, and to a shallow layer near the freezing level in a dissipating thunderstorm. Icing in cumuliform clouds is usually clear or mixed[24].

c. **Other.** Aircraft icing rarely occurs in cirrus clouds, some of which do contain a small proportion of water droplets. However, icing of light intensity has been reported in the dense cirrus anvil-tops of cumulonimbus, where updrafts may maintain considerable water at rather low temperatures.

20. Frontal Systems. It is rather difficult to represent frontal icing conditions by an idealized model, since the structure of the clouds in frontal regions and in regions of intense low-pressure systems is very complex [21]. In general, frontal clouds have a higher icing probability than other clouds. It has been estimated [41] that 85% of the observed aircraft icing occurs in the vicinity of frontal zones. Usually, the greatest horizontal extent of icing is associated with warm fronts, and the most intense icing with cold fronts.

a. **Warm Frontal Icing.** This may occur both above and below the frontal surface. Moderate or severe clear icing usually occurs where freezing rain or freezing drizzle falls through the cold air beneath the front. This condition is most often found when the temperature above the frontal inversion is warmer than 0°C and the temperature below is colder than 0°C [29]. Icing above the warm-frontal surface, in regions where the cloud temperatures are colder than 0°C, is usually confined to a layer less than 3,000 feet thick [21]. Jones [22] found a definite possibility of moderate icing, usually mixed or clear, within 100 to 200 miles ahead of the warm-front surface position. This was particularly noticeable for fast-moving, active, warm fronts. Light rime ice was noted in the altostratus up to 300 miles ahead of the warm-front surface position.

b. **Cold Frontal Icing.** Whereas warm-frontal icing is generally widespread, icing associated with cold fronts is usually spotty [31]. Its horizontal extent is less, and the areas of moderate icing are localized. Clear icing is more prevalent than rime icing in the unstable clouds usually associated with cold fronts [22]. Moderate clear icing is usually limited to supercooled cumuliform clouds within 100 miles to the rear of the cold-front surface position, and is usually most intense immediately above the frontal zone [44]. Light icing is often encountered in the extensive layers of supercooled stratocumulus clouds which frequently exist behind cold fronts. Icing in the stratiform clouds of the wide-spread anafront type of cold-front cloud-shield is more like icing associated with warm fronts.

c. **Other.** Icing conditions associated with occluded and stationary fronts are similar to those of a warm or cold front, depending on which type the occlusion or stationary front most resembles. Moderate icing conditions are frequently associated with deep, cold, low-pressure areas in which the frontal systems are quite diffuse [44].

21. Airmass. The characteristics of icing, being primarily dependent on cloud type and temperature, vary from one airmass to another. Icing is more prevalent in maritime than in continental airmasses, and is more hazardous in regions of instability [7].

22. Dew-Point Spread. Statistics from a number of sources suggest that the radiosonde-measured, analyzed, or forecast dew-point spread at flight level can be used as an indicator of aircraft-icing occurrence. Table 2, adapted from *WADC Technical Note WCT 55-26* [44], shows the probabilities of icing occurrence and intensity as related to the radiosonde dew-point spread, the flight-level thermal advection[1], and the presence of building cumuliform clouds. These data were collected by various types of aircraft during all-weather flight tests east of the Mississippi River, and were summarized irrespective of altitude and temperature. (It is important to note here that the dew points used in these data are those measured by US radiosonde instruments with lithium-chloride hygrometric elements.)

a. Considering only the dew-point spread, there was an 84% probability that there would be *no* icing if the spread were greater than 3°C, and an 80% probability that there *would be* icing if the spread were $\leq$ than 3°C. (See Figure 7, Figure 16, and Tables 8 and 9 in attachment 1, for further data on icing frequency with respect to dew-point spread.)

b. The type of thermal advection or the presence of building cumuliform clouds, taken in conjunction with the dew-point spread, showed a definite association with the occurrence and intensity of aircraft icing.

(1) When the dew-point spread at flight level was 3°C or less in areas of warm-air advection, there was a 67% probability of *no* icing, 20% and 13% probabilities of trace and light icing, respectively, and no probability of moderate icing. By contrast, when the dew-point spread was 3°C or less at flight level in a cold-frontal zone (frequently an area of intense cold-air advection), the probability of icing approached 100%. There was also nearly 100% probability of icing in building cumuliform clouds when the dew-point spread was 3°C or less.

[1] Advection is defined here as the rate at which the isotherms appear to be transported by the upper-level contours, i.e., $-(\mathbf{v} \cdot \nabla T)$ at flight level.

TABLE 2

Icing Intensity as Related to Radiosonde Temperature Dew-Point Difference. (Probability in percent.)

Condition of Flight Level	Temperature Dew-Point Difference						
	≤ 3°C					> 3°C	
	No Icing	Trace Icing	Light Icing	Moderate Icing	Severe Icing	No Icing	Trace Icing
Cold-Frontal Zone*	0	18	45	35	2	67	33
Cold-Air Advection	10	33	44	13	0	54	46
Neutral Advection	22	46	29	3	0	100	0
Warm-Air Advection	67	20	13	0	0	100	0
Building Cumulus	0	6	70	24	0	--	--
Overall	20.5	30.5	35.5	13.0	0.5	84.0	16.0

* Most intense cold-air advection occurs in cold-frontal zone.

(2) With a dew-point spread greater than 3°C, trace icing was about 40% probable in regions of cold-air advection while there was almost 100% probability of *no* icing in regions of neutral or warm-air advection.

c. When compiling data for inclusion in tables 2 and 3, WADC personnel [44] found considerable scatter in the relation of icing occurrence to dew-point spread. They subjectively selected 3°C spread as a convenient dividing line between large probabilities of icing or of no-icing. WADC representatives have stated in verbal communication that their further experience indicates that a 4°C dew-point spread might be a more operationally realistic division point.

(1) The above study should be compared with the study by Johannessen [49] at this headquarters, (see AWSTR 231), in which it was found that at 500 mb a (US radiosonde) dew-point spread of four degrees or less is indicative of the probable presence of clouds. This result suggests that the WADC test flights, having intentionally sought out icing conditions, are weighted in favor of clouds with a high probability of icing, and therefore the WADC 3°C to 4°C spread limit practically coincides with Johannessen's limit for probable presence of clouds. A more random sample of flight data would probably show a smaller limiting spread for icing than for mere presence of clouds, and considerably smaller icing proabilities than WADC found. (The reason why clouds occur with radiosonde spreads greater than zero is explained in AWSTR 231.)

(2) An unpublished study by Cushman at this headquarters based on AWS weather-reconnaissance data at 700 mb and 500 mb (a portion of the same data used by Perkins, Lewis, and Mulholland [37]) is also of interest. The limiting dew-point spread value which included most of the icing cases was found to range from 0° at 0°C to 4° at -20°C (see attachment 1, Figure 16). This apparent general agreement with the WADC and Johannessen studies may be only fortuitous since the correlation between reconnaissance-measured dew-point spread and radiosonde-measured dew-point spread is quite unknown; however, it is believed that for a statistical comparison such as this, the mean radiosonde and reconnaissance data are compatible in this range of temperature and humidity.

(3) Therefore, for temperatures near -10°C to -15°C one may generally assume that a dew-point spread of 4°C or less should be indicative of probable clouds, and that a spread of about 2°C or 3°C, or less, should be

indicative of probable icing. (Figure 7, table 8, and paragraph 36, summarize in more detail, the most reasonable inferences on relation of icing probability to dew-point spread and temperature.) Further empirical experience might recommend varying the dew-point spread limit according to different aircraft types, but at present, forecasters would be justified only in varying the limit with temperature as shown by the AWS reconnaissance data.

23. Presence of Precipitation. Based upon the Bergeron-Findeisen theory that ice crystals were necessary in cold clouds to produce precipitation, Lewis[27] concluded that the presence of steady precipitation at the surface should be an indication that aircraft icing in clouds over such areas would be relatively light. During NACA flight tests [26] to measure the physical properties of icing, a trace of ice was reported in 80% of the observations in clouds over steady precipitation areas and light icing was reported in only 20% of the observations. In stratiform clouds over areas without precipitation, the observed percentages were just the reverse. However, others, e.g., WADC [44], found that the presence of precipitation does not necessarily mean that the icing will be trace. If the vertical motion caused by frontal slopes, terrain, or surface heating is sufficient to maintain a constant supply of supercooled water droplets, light, or even moderate, icing can be present in clouds over areas of steady precipitation. Table 3, based on WADC all-weather flight-test data [44], shows the probabilities of various intensities of icing when the dew-point spread at flight level is 3°C or less and precipitation is present. Icing occurred in 67.5% of the cases when there was no precipitation and 94.5% of the cases when there was precipitation.

TABLE 3

Icing Intensity as Related to the Presence of Precipitation [44].
(Probability in percent)

Condition at Flight Level	Radiosonde Temperature Dew-Point Difference $\nless 3^{\circ}$C									
	Precipitation Absent					Precipitation Present				
	No Icing	Trace Icing	Light Icing	Moderate Icing	Severe Icing	No Icing	Trace Icing	Light Icing	Moderate Icing	Severe Icing
Cold-Frontal Zone*	0	32	55	13	0	0	5	35	56	4
Cold-Air Advection	15	18	52	15	0	3	50	37	10	0
Neutral Advection	41	38	21	0	0	9	52	34	5	0
Warm-Air Advection	75	13	12	0	0	11	67	22	0	0
Building Cumulus	0	0	77	23	0	0	25	50	25	0
Overall	32.5	22.5	37.0	8.0	0.0	5.5	40.5	34.5	18.5	1.0

*Most intense cold-air advection occurs in cold-frontal zones.

24. Orographic Influence. High or steep terrain, particularly mountains, causes icing to be more intense than is usual under identical conditions over low, flat terrain [22][40]. Icing is greater over the ridges than over valleys and greater on the windward side than on the leeward side. Moderate icing, usually clear, is experienced in convective clouds over mountainous terrain. Windward, mountainous coasts in winter are especially subject to extensive aircraft-icing zones. The lifting of the fresh maritime polar air by the mountains results in the formation of more-or-less continuous supercooled clouds. Also, the orographically-induced updrafts permit the air to support larger cloud droplets than otherwise, so that the icing is more intense.

25. Geographic Distribution. There is a wide variation between geographic areas in aircraft-icing potential due to area-to-area variations in temperature and available mois-

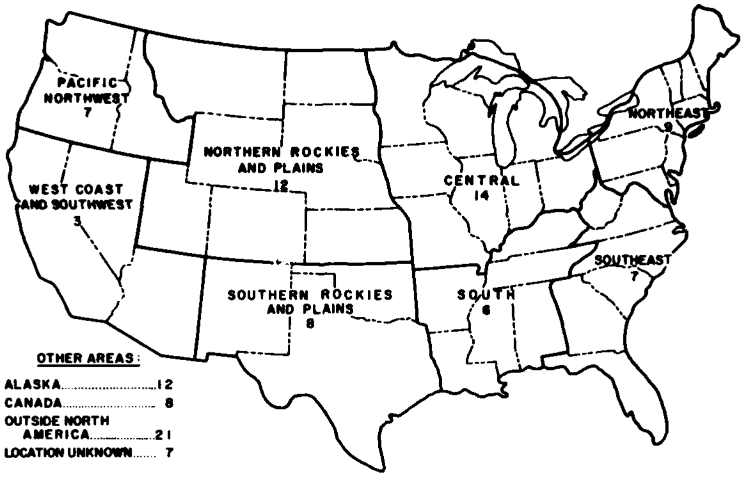


Figure 2—Geographical Distribution of USAF Aircraft Accidents in Which Icing was a Factor, 1 January 1946 through 31 December 1958.

ture. For example, icing during the winter season is very frequent over the warm-water areas off the east coast of continents, to the lee of large inland water bodies, and over those western portions of continents where winds transport ample moisture inland from the oceans [7][23][30][35][36]. Because of the comparatively small amount of moisture in winter arctic air and the small liquid-water content of clouds, icing is seldom regarded as a serious problem in the arctic in winter [38]. It is not surprising, therefore, that icing was reported by weather-reconnaissance aircraft only 2% of the time over the Arctic Ocean at 10,000 feet. On the other hand, at the same altitude over the northern portion of the North Atlantic Ocean, icing was reported 19% of the time.

a. In a NACA study [37] of USAF weather-reconnaissance data at 700 and 500 mb over the oceans, the greatest winter-icing frequency was found over the northern and western parts of the North Pacific and North Atlantic[2], and the least over the Arctic Ocean. This does not imply that icing is never a hazard in the arctic. In those instances when moisture-laden air from the North Atlantic and the North Pacific invades the arctic, conditions conducive to copious ice are established.

b. The distribution of Air Force aircraft accidents in which icing was a factor is shown in figure 2 for the 13-year period ending 31 December 1958 [17]. The greatest number of such accidents occurred in the Central United States while the Northern Rockies and Plains ranked second. An NACA study [35] of icing reports by civilian airlines in the US showed similar results.

26. Seasonal Distribution. Generally speaking, winter is the season of maximum, and summer the season of minimum, aircraft-icing frequency. A similar seasonal variation is also evident in the incidence of Air Force aircraft accidents involving icing. Of the 114 aircraft accidents occurring from 1946 through 1958 in which icing was a factor, 56 occurred in winter, six in summer, 25 in spring, and 27 in the fall.

a. At 700 mb. In the vicinity of this pressure surface, there is relatively little seasonal variation over the northern portions of the North Atlantic and North Pacific Oceans, which have a relatively high climatological frequency of icing. However, comparatively large seasonal variation is found over the other ocean areas. Winter is the season of maximum icing (more suitable temperatures) in these other areas, except over the Arctic

[2] The ocean areas considered in this discussion are the Atlantic and Pacific Oceans north of 20°N and the Arctic Ocean.

Ocean which has the maximum in summer [37] (temperature and moisture too low in winter).

b. At 500 mb. Because temperatures are almost always below freezing at 500 mb, seasonal variations of icing at altitudes near this pressure surface are more dependent on the seasonal variations of moisture than of temperature. The summer-season icing maximum over the Arctic Ocean and the northern and western portions of the North Atlantic and North Pacific Oceans results from the higher moisture content of the air in summer than in the other seasons. On the other hand, the maximum icing over the eastern ocean areas is found in the fall, the season of greatest cyclonic and convective activity.

Chapter 5

NON-SYNOPTIC FORECAST AIDS

★27. **General.** The previous chapter discussed the distribution of icing mainly as a function of the synoptic situation and ordinarily observed meteorological elements. The present chapter describes a number of non-synoptic forecast aids and parameters computed from synoptic or aircraft data. Included are information on the use of radar and radiosonde data to determine the location and intensity of regions of potential aircraft icing, theoretically and empirically determined aerodynamic-heating curves for various aircraft, and statistically determined curves of the frequency of aircraft icing as a function of altitude and temperatures.

★28. **Radar Weather Observations.** The presence of icing conditions in an area can frequently be inferred from ground-based storm-detection and cloud-detection radar.

a. The range-height indicator (RHI) of a storm-detection radar displaying a vertical cross-section of a precipitation area will often exhibit a horizontal bright band. The AN/TPQ-11 Cloud Detection Radar will similarly show a peak amplitude on the A-scope and on the recorder. The bright band is generally recognized as indicating the level where the precipitation from snow and ice crystals above the band changes to water drops below. Proper interpretation of the bright band must be supported by the knowledge of the type of cloud being detected by radar.

(1) Bright bands are frequently seen in stratiform clouds and depict the melting level where precipitation changes from ice crystals to water droplets. When such stratiform clouds surround thunderstorms and rain showers, the bright band can approximate the height of the freezing level. Strong vertical motions within developing cumulus clouds destroy the bright band as liquid water droplets are lifted and supercooled above the 0°C isotherm. The most severe icing is found near the top of cumulonimbus clouds. Radar echoes from such clouds can have maximum liquid water content, and temperature may be 10 or 15 degrees below freezing.

(2) An aircraft will often encounter dry snow above the bright band in weak echoes. Exceptions will be found when there is sufficient high-level instability to cause the formation of supercooled water drops to give icing. These clouds composed of small particles will not show strong echoes but would create light icing conditions. Supercooled clouds are often found above and occasionally adjacent to radar echoes from snow. In such cases, no icing would be expected within the radar echoes from the snow.

(3) Below a bright band, one can expect only rain with no icing unless the temperature drops below freezing again at the lower elevations, which results in freezing rain and sleet. Radar alone cannot identify such a condition. When the entire atmosphere above the ground is below freezing, all radar echoes will be from snow and cause no icing.

(4) Icing potential cannot be inferred by the detection of a bright band alone. The radar operator must identify the type of cloud and its motion before an indication of its potential is realized. When used with supporting data on temperature and moisture, radar adds an important dimension to icing forecast capability.

b. The use of weather radar observations is described in more detail in various publications.

(1) AWSTR 180, Preliminary Operational Application Techniques for the AN/TPQ-11; AWSTR 184, General Application of Meteorological Radar Sets; and AWSTR 223, Operational Utilization of the AN/TPQ-11 Cloud Detection Radar cover the interpretation of weather radarscope displays under operational conditions.

(2) Nonmilitary publications are Atlas [6], Battan [8], Hiser [50]. Parts A and B of Weather Radar Manual (WBAN), August 1967 [51] prescribe the procedure and plain language code form used in reporting radar weather observations.

29. **Liquid-Water Content.** Observations and theoretical studies indicate liquid-water content is an important parameter in icing.

a. **Cumuliform Clouds.** Estimates of a practical upper limit of the liquid-water content (LWC) in cumuliform clouds at flight level can be made from the following formula:

$$\mathrm{LWC} = \frac{1}{2.87}(W_0 - W_1)\frac{P}{T}$$

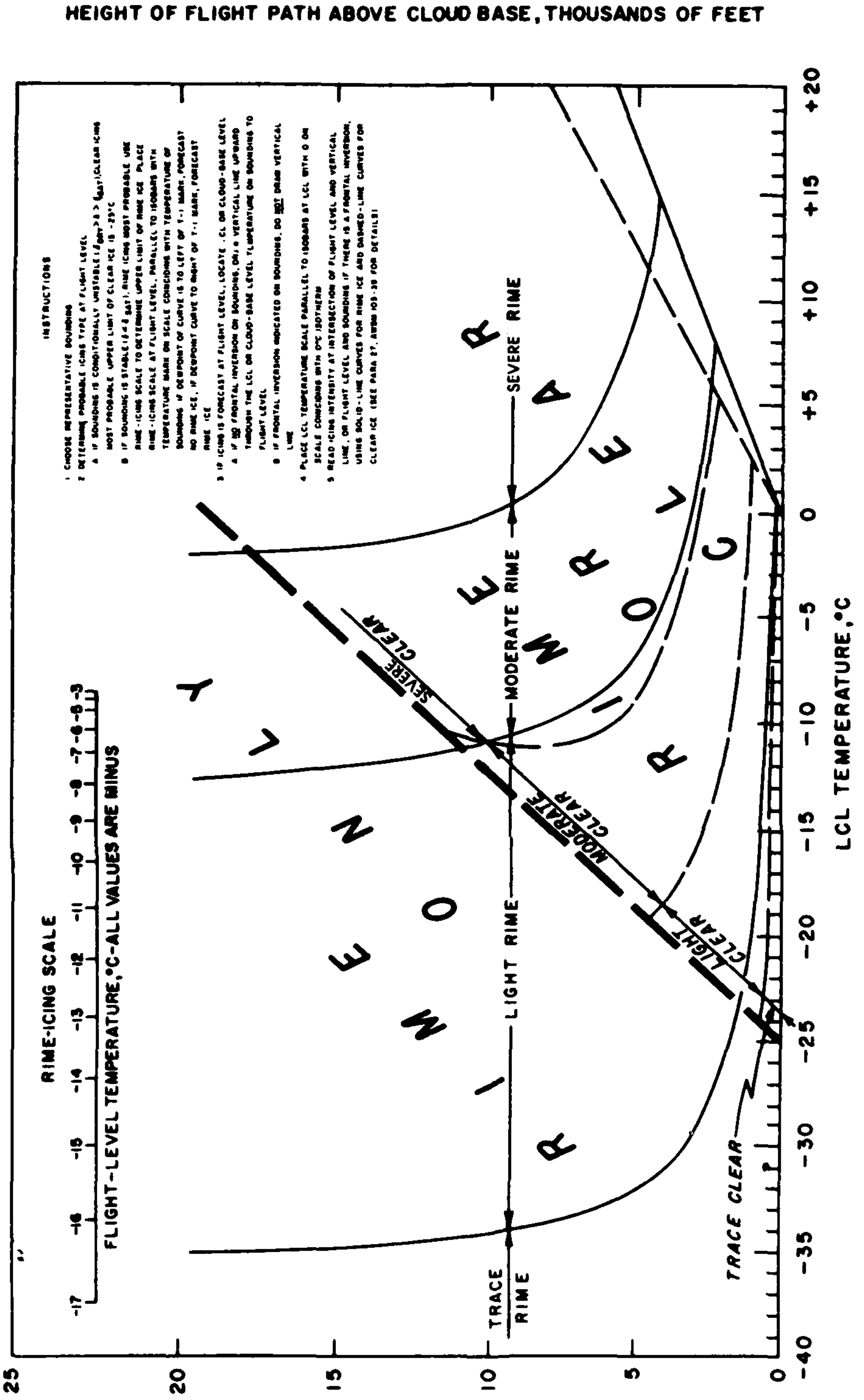


Figure 3a—An Overlay for Use with the Skew T, Log P Diagram, AWS WPC 9-16, to Determine the Most Probable Icing Intensity to be Expected in Cumuliform and Stratiform Clouds. (Local reproduction of this diagram is authorized. Full-scale model appears at the back of this manual.)

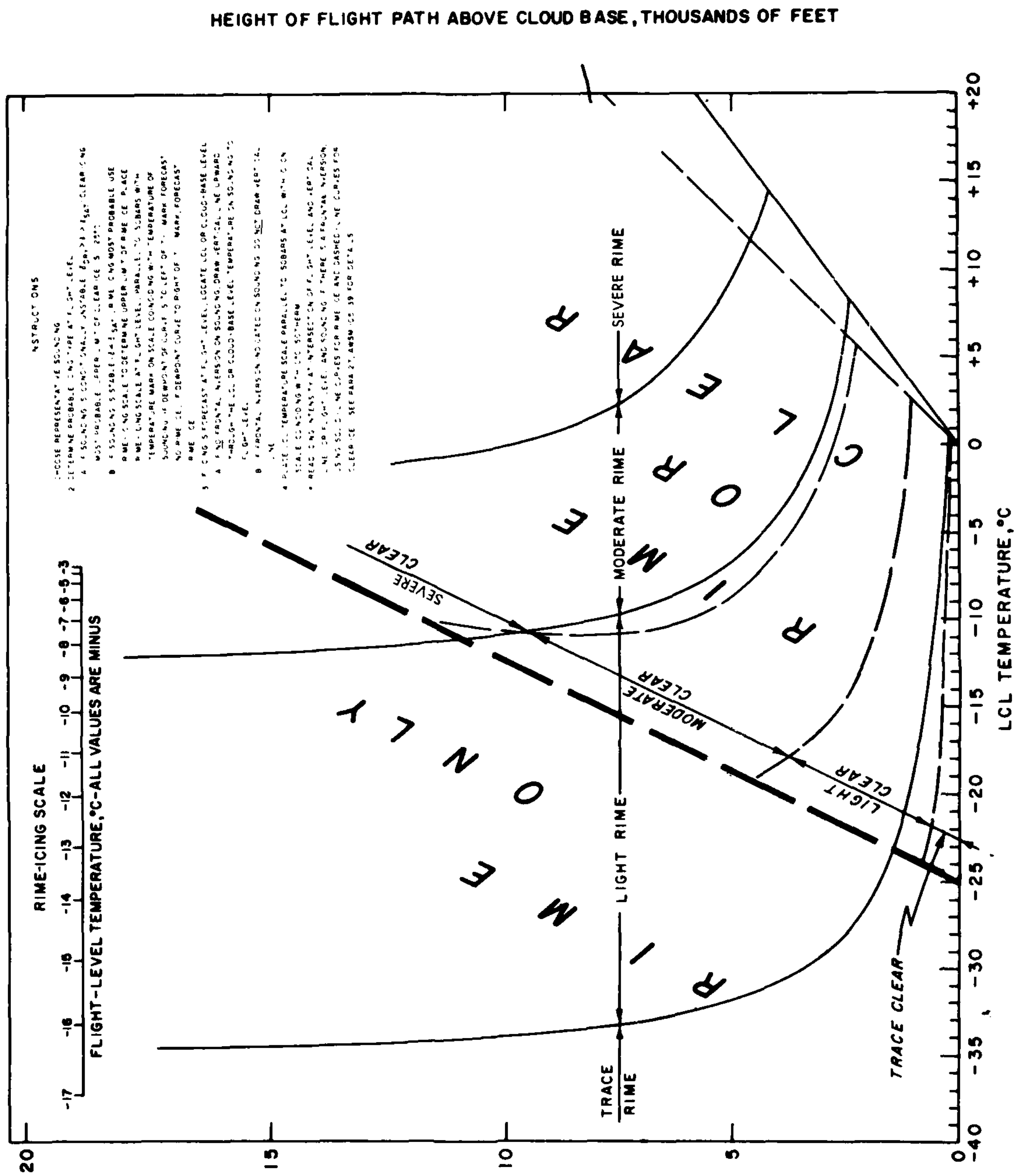


Figure 3b—An Overlay for use with the Skew T, Log P Diagram, AWS WPC 9-16A, to Determine the Most Probable Icing Intensity in Cumuliform and Stratiform Clouds. (Local reproduction is authorized. Full-scale model appears at the back of this manual.)

in grams per cubic meter, where

W_0 = **saturation mixing ratio at cloud base (gm/kgm)**

W_1 = **saturation mixing ratio at flight level (gm/kgm).**

P = **atmospheric pressure at flight level (mb).**

T = **cloud temperature at flight level (°K).**

2.87 = **a constant of proper dimensions to balance the units in the equation.**

b. **Stratiform Clouds.** The liquid-water content found in stratiform clouds averages about half the value computed using the above formula[10].

c. **Relationship to Icing Intensities.** The mean effective droplet size is usually slightly less for stratiform than for cumuliform clouds. Therefore, the liquid-water content values also have a different relationship to icing intensities in the two cloud forms[27]. These differences are shown in figures 3a and 3b by the different sets of lines for clear and rime icing. The relationship between liquid-water content and icing intensities based on the data used in preparing figures 3a and 3b is shown in table 4, taken from NACA[27]. The intensities forecast by the subjective rules used in this manual imply these liquid-water contents and not the actual operational effect upon the aircraft (see paragraph 3).

30. Icing Forecast Aid Based on Liquid-Water Content. The forecast aid shown in figures 3a and 3b (after Cox[16]) is based on considerations of liquid-water content, and provides a means of using the Skew T, Log P Diagram directly in the forecasting of icing. These charts are most easily applied in the form of a transparent plastic overlay and can be produced locally at the Base Photo Laboratory. Figures 3a, 3b, and 3c were constructed for use with DOD WPC 9-16, 9-16A, and 9-16-1, respectively. The fold-in versions of these figures may be detached from the report for direct-scale reproduction. Procedures for using this overlay are as follows:

a. Choose the sounding which will be representative of the airmass to be flown through -- this may be an upwind sounding or a prognostic sounding.

b. Using the surface temperature and dew-point, locate the lifting condensation level (LCL) and draw a vertical line upward through the LCL to the flight level. To speed up the operation, the intersection of the cloud-base level with the sounding may be used instead of the LCL.

c. Place the overlay on the Skew-T Diagram, and determine the probable icing type.

(1) If the sounding is absolutely stable ($\gamma < \gamma_{sat}$) at flight level, rime icing is more probable.

(2) If the sounding is conditionally unstable ($\gamma_{dry} > \gamma > \gamma_{sat}$) at flight level, clear icing is most probable.

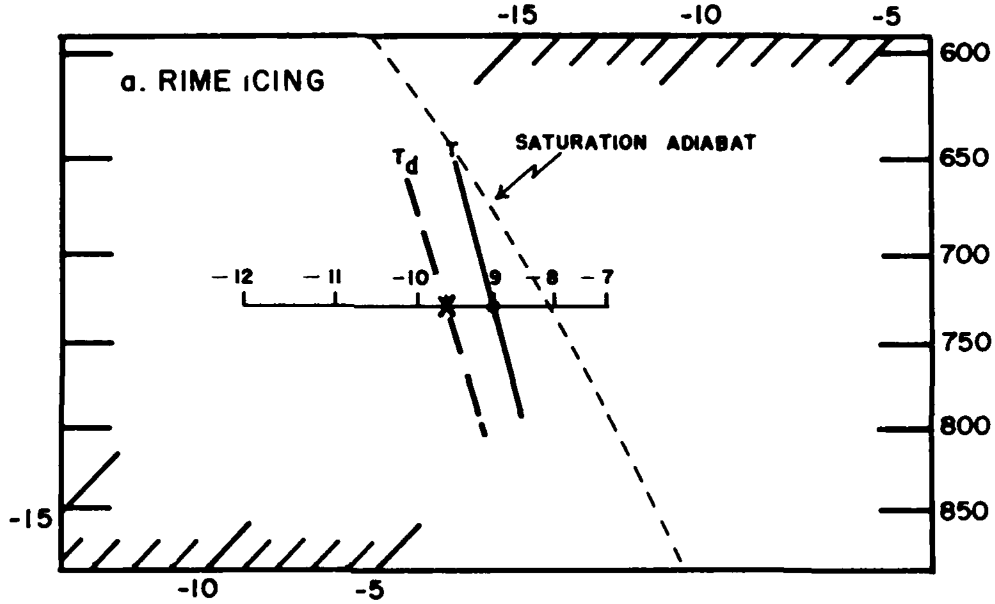
d. Determine the top of the icing layer.

(1) If clear ice is indicated, the upper limit of the icing can be assumed to be the altitude of the -25°C isotherm.

(2) If rime icing is indicated, further manipulation of the overlay is necessary as follows: Place the rime-icing scale parallel to the isobars on the Skew-T, Log P Diagram so that the flight-level temperature value T on the scale (called the temperature mark) is at the flight-level point on the sounding.

(a) If the dew-point curve falls between the temperature mark intersecting the sounding and the next mark to the left on the overlay scale (T - 1°), a forecast of rime icing is appropriate for middle- and low-level stratiform clouds. For example, in figure 4a, the temperature at flight level is -9°C. The rime-icing scale is placed parallel to the isobars, with the -9 mark intersecting the sounding at flight level. The dew-point curve lies between the -9 and -10 marks on the scale, so the forecast is for "rime ice."

(b) If the dew-point curve falls beyond, i.e., further to the left of the (T - °1) mark on the scale, forecast no-rime-icing. For example, in figure 4b, the flight-level temperature is again -9°C, but in this instance the dew-point curve lies to the left of the -10 mark. Hence, the forecast is for "no rime ice."



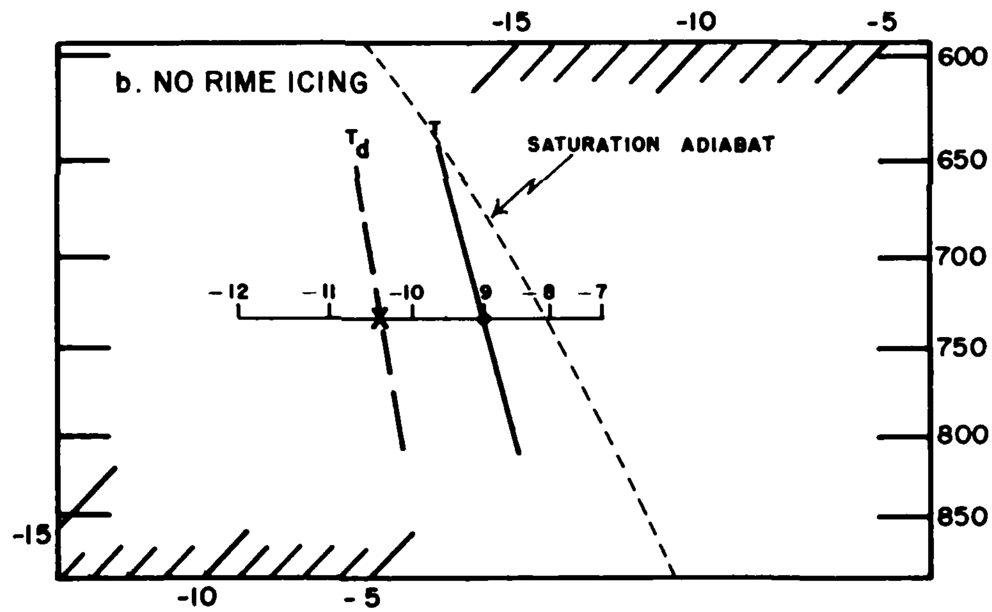


Figure 4—Determinations of Rime Icing by Means of the Rime-Icing Scale Given in Figure 3.

TABLE 4

Relationship of Icing Intensity to Liquid-Water Content

Cumuliform Clouds Liquid-Water Content* gm/m^3	Icing Intensity	Stratiform Clouds Liquid-Water Content** gm/m^3
$\leqslant$ 0.07	Trace	$\leqslant$ 0.11
0.08 - 0.49	Light	0.12 - 0.68
0.50 - 1.00	Moderate	0.69 - 1.33
> 1.00	Severe	> 1.33

* Assumed droplet diameter 17 microns.
** Assumed droplet diameter 14 microns.

e. Superimpose the LCL temperature scale at the bottom of the overlay over the isobar through the LCL of the sounding, so that the zero on the scale coincides with the 0°C isotherm on the Skew-T, Log P Diagram.

f. Determine the most severe icing intensity to be expected, by either of the following:

(1) If the sounding does not indicate a frontal inversion, determine the icing intensity by the zone in which the vertical line through the LCL, drawn in accordance with paragraph 30b, intersects the flight level. Solid lines indicate intensity-zone boundaries for rime-ice cases, and dashed lines for clear-ice cases.

(2) If the sounding indicates a frontal inversion, determine the icing intensity by the zone in which the sounding intersects the flight level. Again, solid lines are used for rime-ice cases, and dashed lines for clear-ice cases.

g. Further examples:

(1) Figure 5a demonstrates an icing situation where no frontal inversion is present. The LCL is located at approximately 970 mb and 2°C, and a vertical line is drawn through the LCL. An inspection of the sounding shows the 0°C isotherm at 920 mb, level A, and the sounding to be conditionally unstable in layers A-C and E-F; therefore, clear icing is expected in these layers with rime icing in layer C-E. The top of the cloud and top of the icing zone are at F, approximately 545 mb and -23.5°C. As shown, an overlay of figure 3a is superimposed on the sounding and the icing intensity zones are determined along the vertical line, as follows: A-B, moderate clear icing; B-C, severe clear icing; C-D, moderate rime icing; D-E, severe rime icing; and E-F, severe clear icing. It must be emphasized that in this case, with no frontal inversion, the icing intensity zones are determined along the vertical line through the LCL.

(2) Figure 5b demonstrates an icing situation with a cold-front inversion overlying the station. The LCL is located at approximately 940 mb and -18.5°C but a vertical line is not drawn since there is a frontal inversion present. An inspection of the sounding shows conditional instability in the layer E-F, where clear ice is expected. Otherwise, the icing will be rime. The top of the cloud and the top of the icing are at approximately 515 mb and -23.5°C. As shown, an overlay of figure 3a is superimposed on the sounding and the intensity zones are determined along the sounding curve itself as follows: A-B, trace of rime icing; B-C, light rime icing; C-D, moderate rime icing; D-E, severe rime icing; and E-F, severe clear icing.

31. Cloud Phase:

a. The theoretical presence of supercooled liquid-water droplets, particularly in

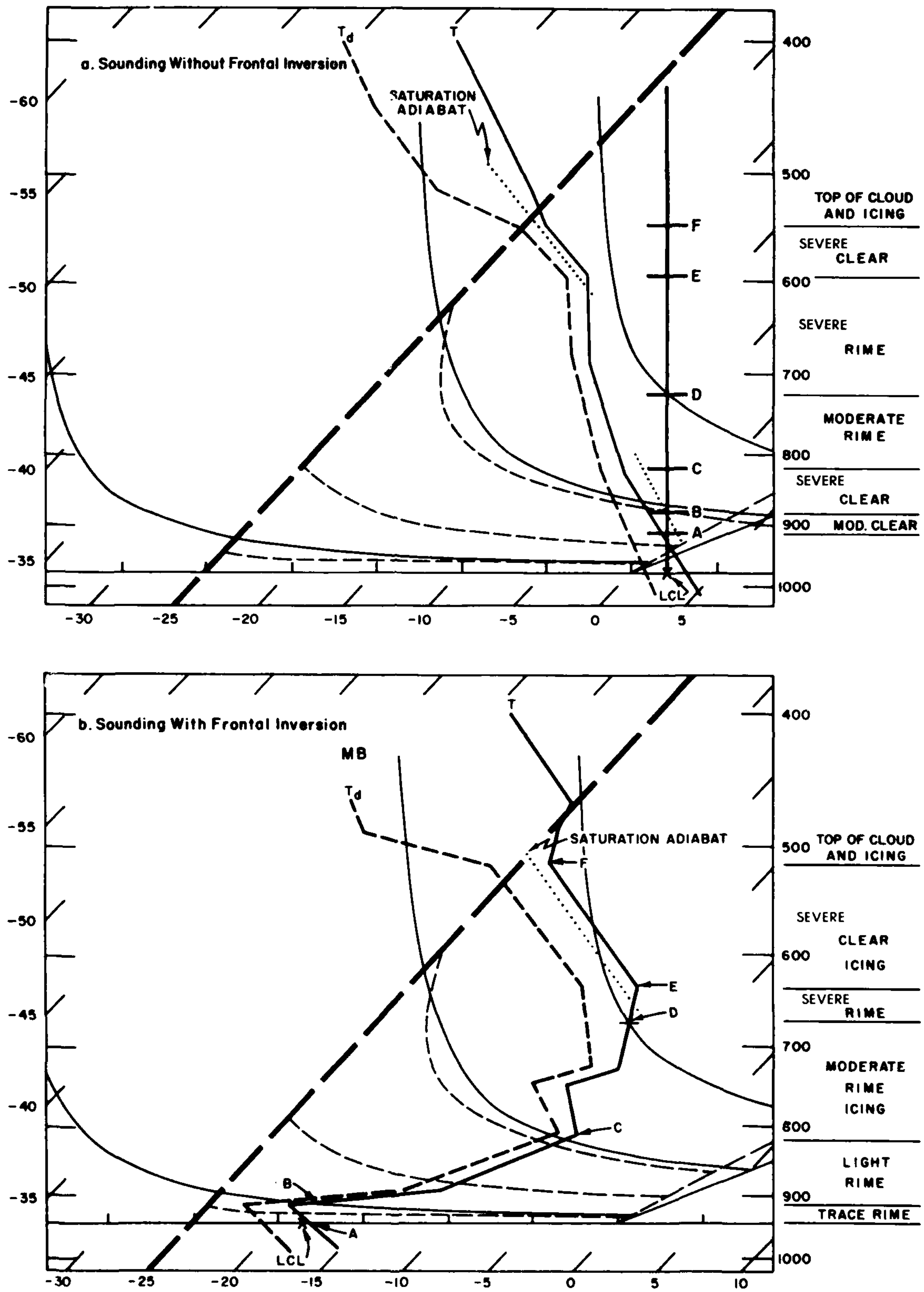


Figure 5—Illustrations of Icing Intensity Determinations by Means of the Overlay from Figure 3.

stratiform clouds, can be estimated from the relationship of the temperature to the frost point (the highest temperature at which atmospheric moisture will sublimate in the form of hoarfrost on a cooled, polished surface). Unless there is sufficient upward vertical motion to maintain a continuous production of supercooled liquid-water droplets, the cloud will generally change its phase with time from a liquid-water cloud to a mixed water-and-ice cloud and finally to an ice-crystal cloud.

b. If the radiosonde instruments in use were perfect, the relationships between the cloud phase, the relative humidity, and the associated dew points and frost points would be as given in tables 5 and 6. Also, the phase of a stratiform cloud existing at below freezing temperatures could be determined by plotting the temperature, dew-point and frost-point curves on a Skew-T, Log P Diagram as illustrated in figure 6.

(1) In the layer between A and B in figure 6, the relative humidity is 100% with respect to water. Clouds in this layer would be composed entirely of water droplets, and icing would be very probable.

(2) In the layer between C and D in figure 6, the relative humidity is less than 100% with respect to water but greater than 100% with respect to ice in those regions where the temperature curve lies between the dew-point and frost-point curves. Hence, clouds in this layer should consist of a mixture of liquid-water droplets and ice crystals, and trace of icing would be probable.

(3) In the layer between E and F in figure 6, the relative humidity is 100% with respect to ice where the temperature and frost point coincide. The cloud in this case should be composed of ice crystals, and the resultant icing effects would usually be quite negligible.

(4) Icing would be generally nonexistent when the frost-point curve lies far to the left of the temperature curve (B-C and D-E of figure 6).

c. In actual practice, the radiosonde humudity element frequentlv reads too low in clouds (see AWSTR 231[49]). Therefore, the frost-point curve is almost always to the left of the temperature curve and an allowance must be made if the actual plot of the temperature, dew-point, and frost-point curves are used to determine the phase of a stratiform cloud. This is in agreement with the findings of Teteryukov[43], who states that icing often occurs in clouds with relative humidities reported to be as low as 80% with respect to water.

d. A rapid and practical application of the frost-point technique to stratiform clouds is possible using figure 7, revised from Appleman[5] to accommodate the larger sample of data in Cushman's analysis of AWS weather-reconnaissance observations reported in attachment 1.

TABLE 5

Cloud-Phase Relationships*
(T = Temperature, T_d = Dew Point, T_f = Frost Point)

Cloud Phase	Relative Humidity (RH)	Parameters
Liquid-water droplets	100%/water = RH > 100%/ice	$T_d = T < T_f$
Mixed	100%/water > RH > 100%/ice	$T_d < T < T_f$
Ice crystals	100%/water > RH = 100%/ice	$T_d < T = T_f$

* Perfect radiosonde instruments are assumed (Appleman [5]).

(1) The approximate percent frequencies of icing occurrence indicated for several areas of the diagram are based on these reconnaissance data. The roughly trapezoidal area between the $T = 0.8T_d$ line and the dashed line parallel to it at colder dew points, con-

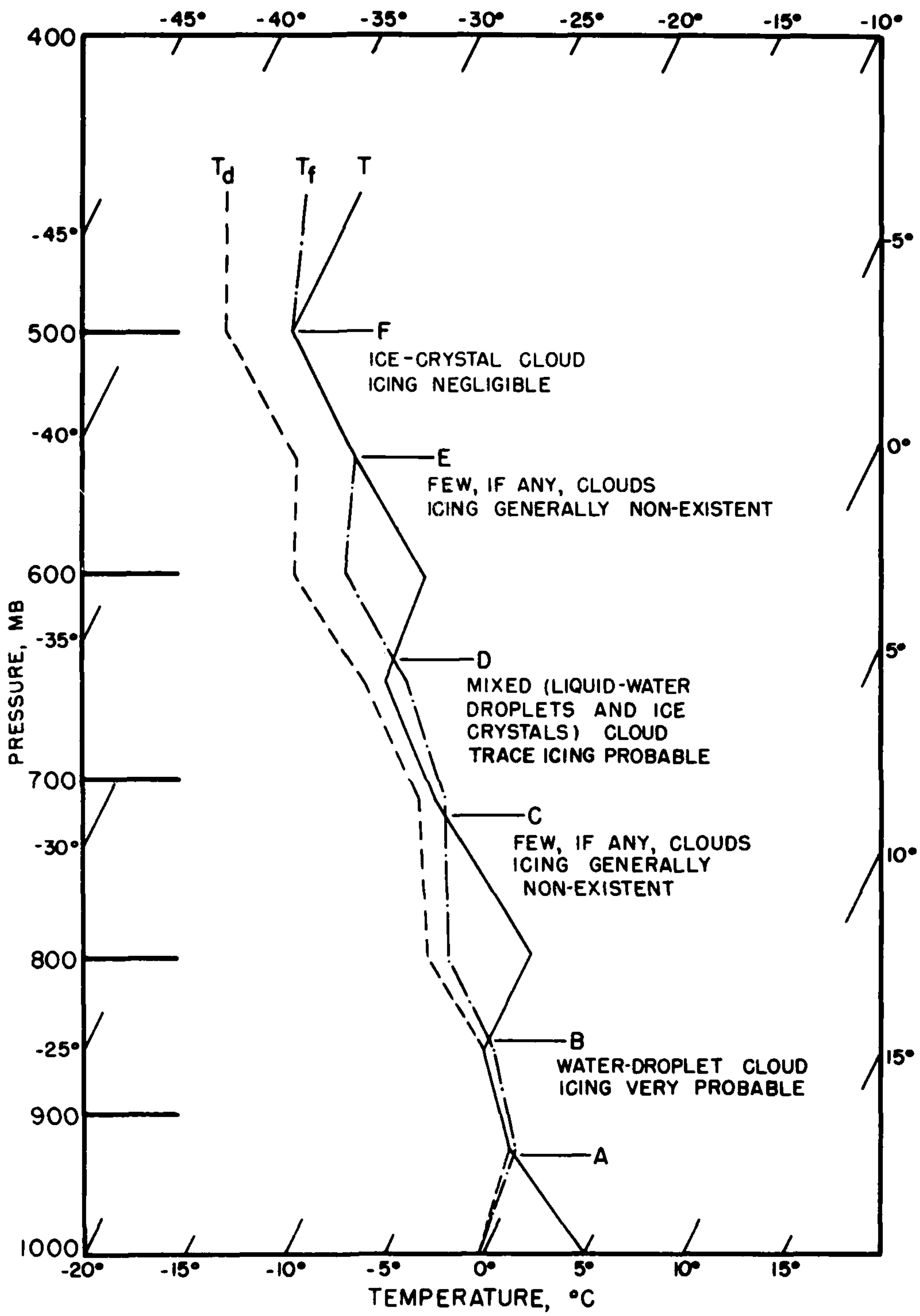


Figure 6—Example of Cloud-Phase from Skew T, Log P Diagram (Perfect radiosonde instrument assumed).

TABLE 6

Approximate Water- and Ice-Relative Humidity Relationships

If RH/Water = 100%, RH/Ice (%) would be	Temperature (°C)	If RH/Ice = 100%, RH/Water (%) would be
100	0	100
105	-5	95
110	-10	91
116	-15	86
122	-20	82
128	-25	78
134	-30	75
141	-35	71
147	-40	68

(Based on Tables 100 and 101, Smithsonian Meteorological Tables, 6th Revised Edition, 1951.)

tained sufficient observations and icing cases to require labeling it as an "icing probable" area. The large dew-point spreads in this area presumably represent extremely inaccurate dew-point observations, especially since Johannessen found that a 4° dew-point spread is usually the limit for indication of clouds in radiosonde ascents [49], or measurements made in the clear air between clouds during flights under intermittent icing conditions. Appleman's sample [5] of data was too small to show clearly the frequency of these extreme cases.

(2) It is generally accepted that cumuliform clouds change phase rather rapidly during their growth and dissipation, and hence exhibit wide variability in both space and time. But the stage of devlopment of such clouds is not recorded during routine weather-reconnaissance observations, and radiosonde reporting procedures do not normally indicate whether or not the instrument has passed through a cumulus cloud during its ascent. Figure 7 has been based on data from flights through stratiform clouds. Cushman's analysis of icing frequencies as a function of temperature alone (see footnote 3, attachment 1) showed that icing probabilities in cumuliform clouds are essentially the same as in stratiform clouds. Hence, it is believed that figure 7 can be used successfully as a guide in forecasting icing-occurrence probabilities in any type of clouds.

32. Aerodynamic Heating. For a given aircraft speed, icing protection from aerodynamic-heating effects decreases with altitude due to the decrease in air density. Consequently, the greatest heating occurs when fast aircraft are flying at low levels. The temperature increase is greatest for the leading edge of the wing and least for the portion to the rear of the midchord. The term midchord refers here to the point at which rearward taper of the airfoil begins. In some cases, dynamic heating may be just barely sufficient to prevent ice accumulation on the leading edge of the wing but insufficient to prevent icing to the rear of the midchord if the intercepted cloud droplets flow back over the wing surface.

a. NACA [12][13] conducted experiments to determine the amount of aerodynamic heating to the rear of the midchord for various airspeeds and altitudes. WADC [33] has completed an analysis of the leading-edge icing limit which makes possible the computation of the critical temperature for leading-edge icing. Figures 8, 9, 10, and 11, which show the critical temperatues for the occurrence

of aircraft icing on the leading edge or due to runback for subsonic and transonic speeds, have been constructed using the computations of NACA and WADC. As an illustration of the use of these figures, if the true airspeed of an aircraft at 20,000 feet is 300 knots and the ambient air temperature is -4°C, there will be no icing on the leading edge of the wing (figure 6) but there will be icing to the rear of the midchord due to runback (figure 9).

b. Experiments have also been conducted to determine the effectiveness of aerodynamic heating for removing ice once it has formed.

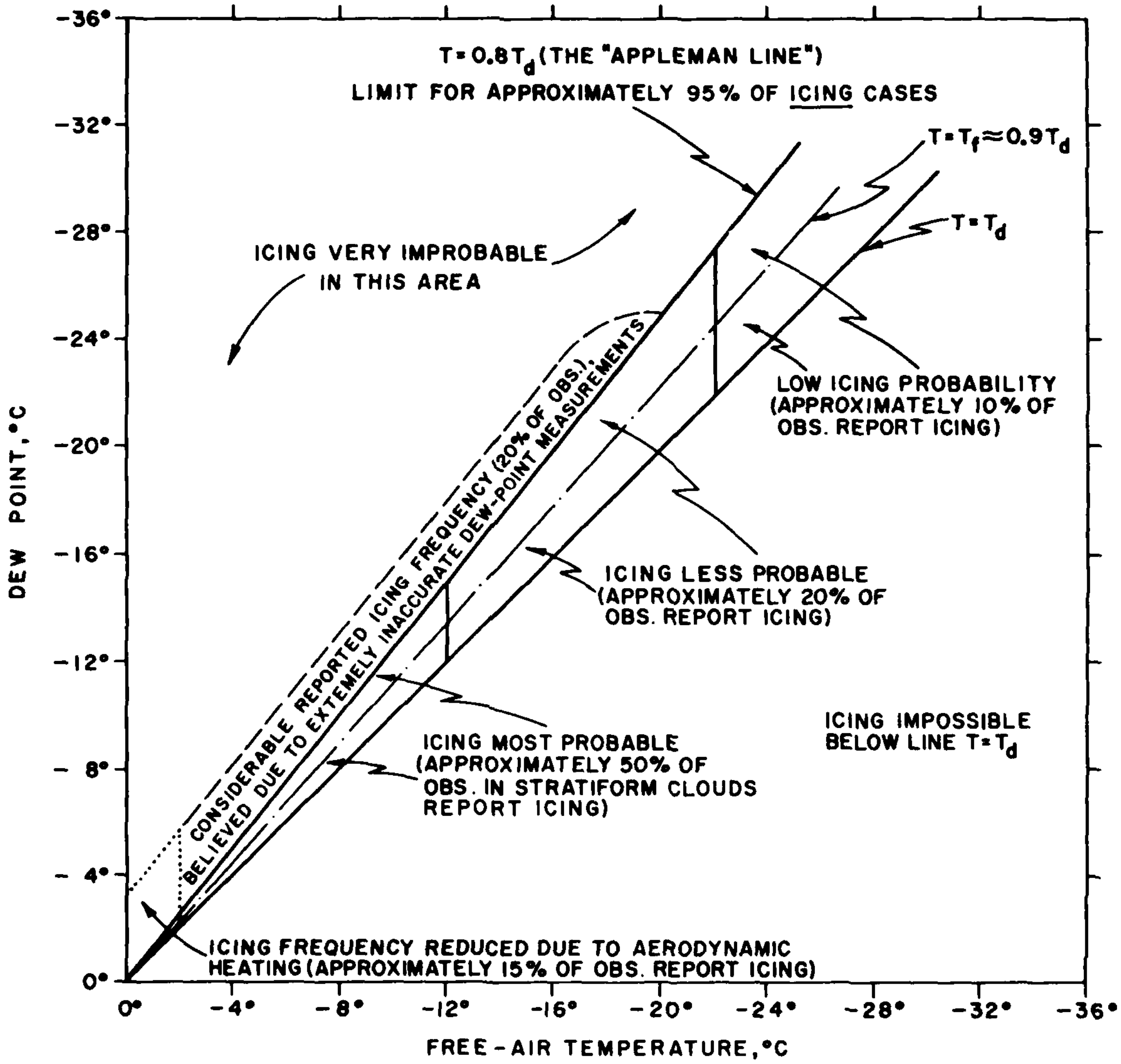


Figure 7—Nomogram for Rapid Application of Frost-Point Technique and Empirical Icing Probabilities to Stratiform Clouds.

NACA [15] found that the removal of ice of appreciable thickness by this process is usually too slow to be of much value in deicing aircraft at high altitudes. WADC[46] conducted flight tests with an F-102 aircraft and verified the NACA experiments, finding that few aircraft of today possess the speed capability required to de-ice surfaces by aerodynamic heating in the clear dry air above the regions where the ice had accumulated.

33. Probability of Icing. Most of the icing statistics available from aircraft reports are biased, either because operational aircraft try to avoid icing conditions or because research aircraft attempt to encounter them. Thus, it is difficult to determine from such reports the true probabilities of icing occurrences under random flying exposure as a function of other parameters (such as cloud and temperature). Reports from AWS reconnaissance aircraft avoid this bias to a large degree, since they fly standard routes at scheduled times and altitudes, with no attempt to avoid or to encounter icing. The probabilities given in figures 12 and 13 (taken from 2 Weather Wing [2]) are based upon an analysis of AWS weather-reconnaissance aircraft icing reports by NACA [37] and are useful if there is only limited information available relative to the flight-level conditions.

a. Figure 12 shows the probable frequency of icing in clouds as a function of temperature and altitude. This graph is useful, provided the presence of clouds at flight level can be forecast. After estimating the extent of a flight in clouds at temperatures colder than freezing, the forecaster multiplies this figure by the probability from figure 12 for the proper altitude and forecast temperature. The resultant value is an estimate of the extent of flights in icing conditions. For example, an aircraft on a 2,000-mile flight at 500 mb and -10°C is expected to be in clouds for 1,200 miles. From figure 12, there is a probability of 35% for icing in clouds at 500 mb and -10°C. Therefore, icing could be expected during 420 miles of the flight. Since such an estimate is based upon mean conditions, icing for any given flight might be either more or less extensive. Usually the use of mean values will be more accurate for long flights than for short flights. For instance, in a relatively short flight, say 200 miles, through a frontal zone or along the windward side of a coastal mountain range, all clouds at temperatures colder than 0°C would have to be considered as potential icing areas. On the other hand, long flights, like the first example, could be expected to approximate the mean conditions.

b. When the presence of clouds cannot be forecast with any appreciable skill over climatology, the graph in figure 13, which assumes a hemispheric statistic climatological frequency of clouds, can be used. For example, if a 2,000-mile flight is planned at 700 mb and -10°C and an estimate cannot be made of the presence of clouds, icing would be forecast for approximately 100 miles of the flight, since the probability given by figure 13 is 5.2% for icing under such conditions.

c. There may be times when it is difficult, if not impossible, due to the lack of data, to forecast the temperatures or the existence of clouds at flight level. When this situation exists and no other forecast aids are available, the probability of icing may be estimated using table 7 (adapted from data contained in NACA Technical Note 3984 [37]). For example, if a 2,500-mile flight is planned at 500 mb in the fall and the temperature and existence of clouds are unknown, icing would be forecast for only 70 miles of flight, since table 7 gives an average probability of 2.8% for icing to occur on flights at 500 mb in the fall.

d. The preparation of estimates of the climatological frequency of icing, where past observations on icing frequency are unavailable or inadequate, is discussed in chapter 7.

TABLE 7

Probable Frequency of Icing as a Function of Altitude.

Season	Probable Frequency Percent	
	700 mb	500 mb
Spring	2.3	1.3
Summer	2.7	2.0
Fall	2.8	2.8
Winter	2.8	2.1

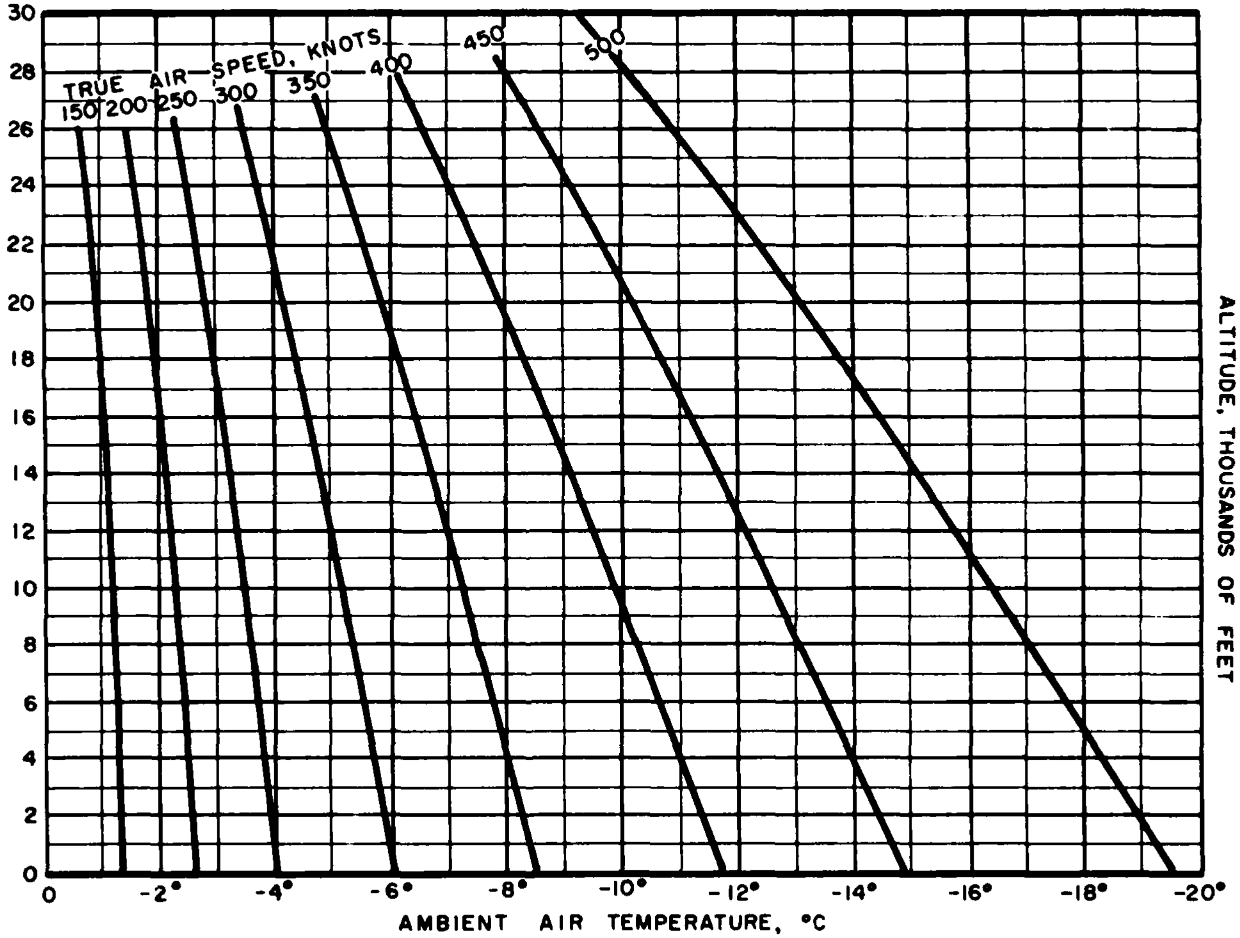


Figure 8—Critical Temperature for Occurrence of Aircraft Icing on Leading Edge of Wing as a Function of Altitude and True Airspeed - Subsonic (Local reproduction of this diagram is authorized.)

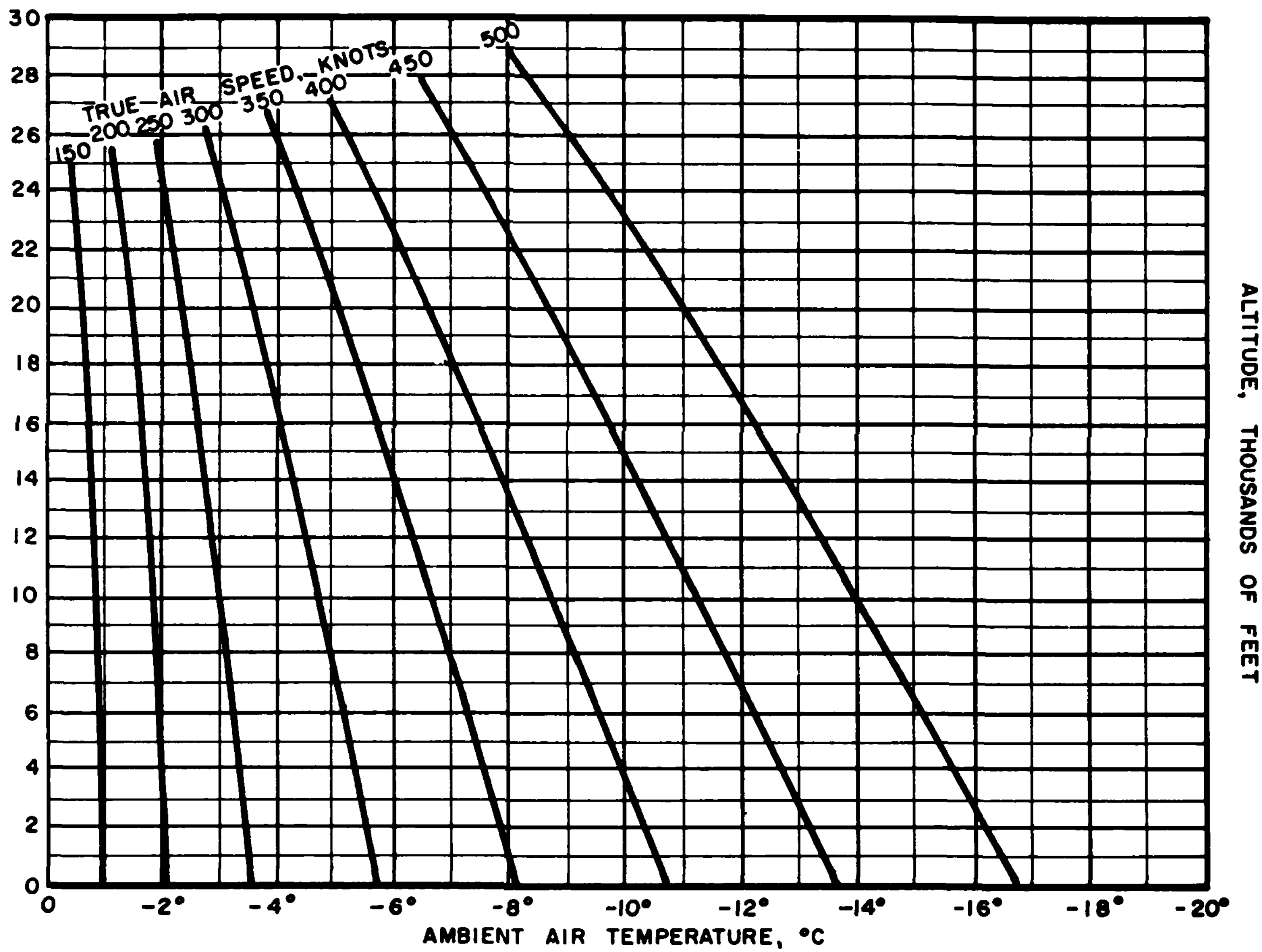


Figure 9—Critical Temperature for Occurrence of Aircraft Icing Due to Runback as a Function of Altitude and True Airspeed - Subsonic (Local reproduction of this diagram is authorized.)

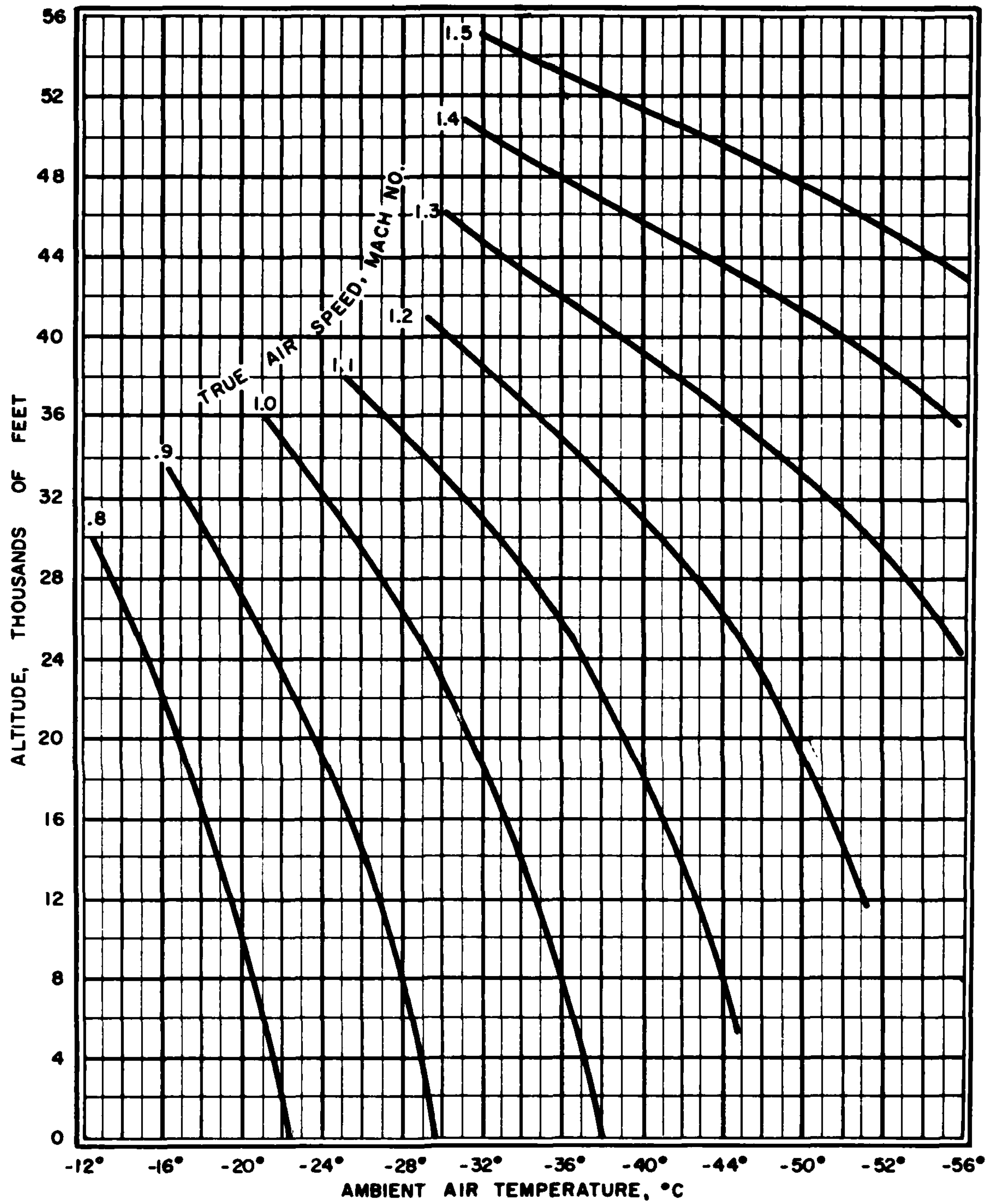


Figure 10—Critical Temperature for Occurrence of Aircraft Icing on Leading Edge of Wing as a Function of Altitude and True Airspeed - Transonic (Local reproduction of this diagram is authorized.)

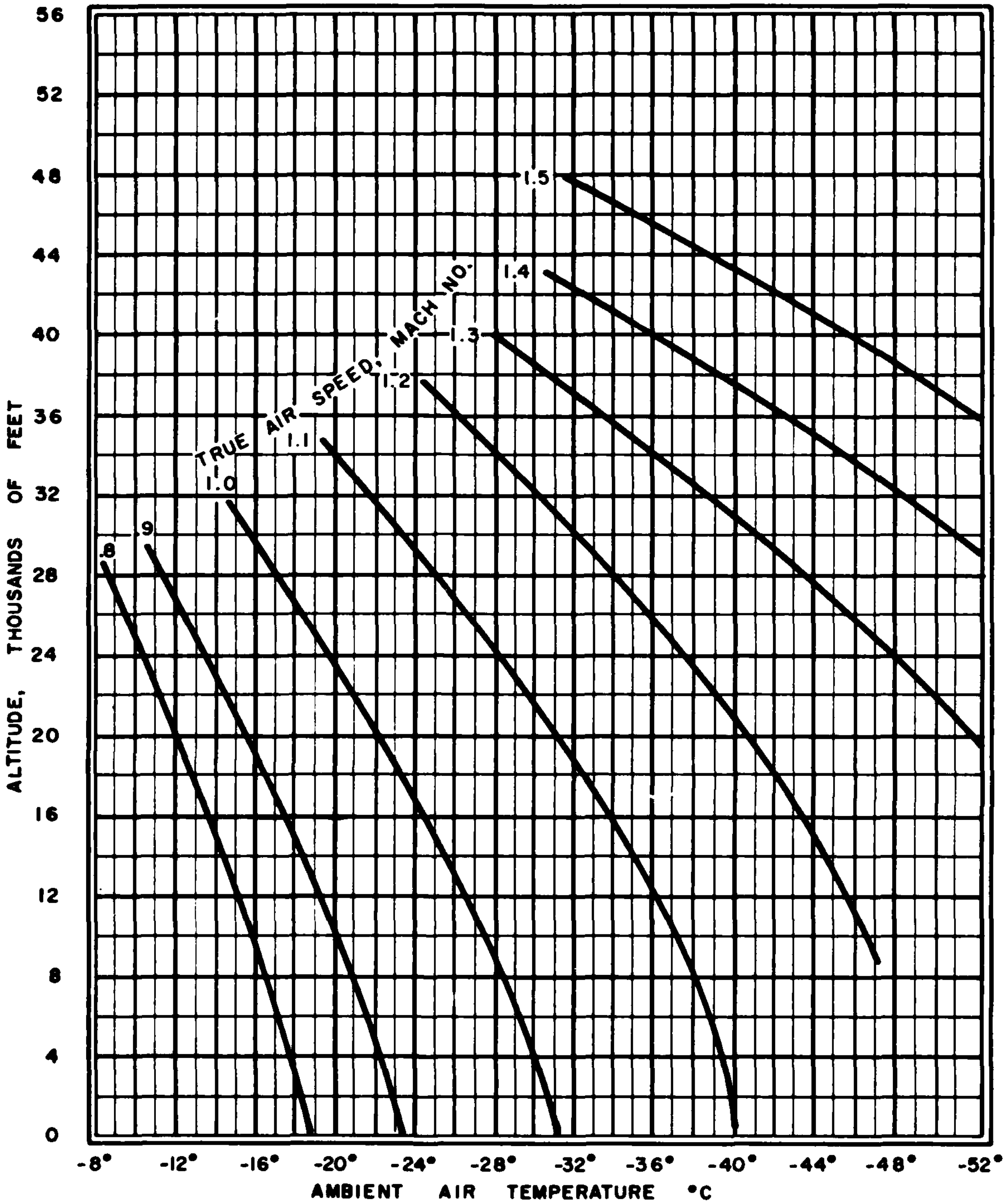


Figure 11—Critical Temperature for Occurrence of Aircraft Icing Due to Runback as a Function of Altitude and True Airspeed - Transonic. (Local reproduction of this diagram is authorized.)

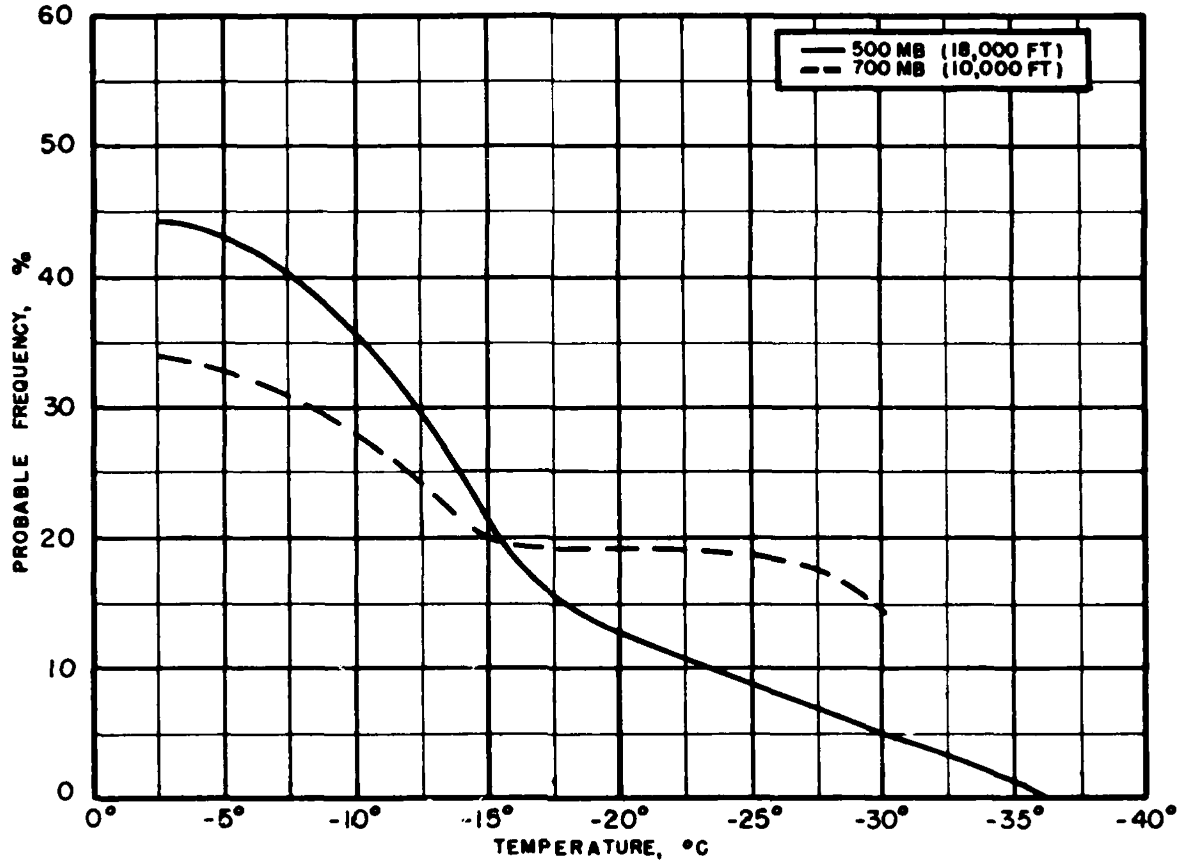


Figure 12—Probable Frequency of Icing in Clouds as a Function of Altitude and Temperature [2]. (Local reproduction of this diagram is authorized.)

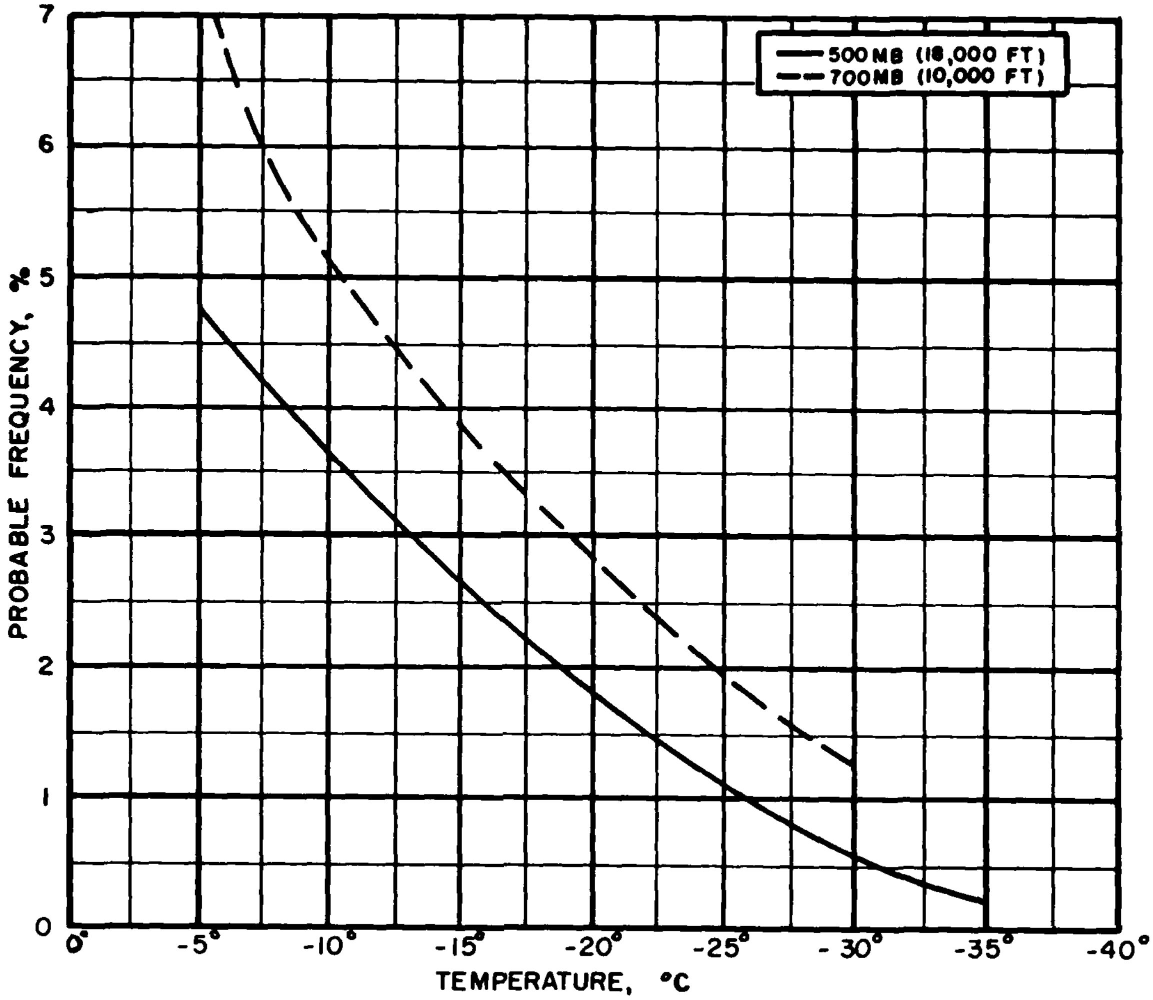


Figure 13—Probable Frequency of Icing as a Function of Altitude and Temperature Without Consideration of Clouds [2]. (Local reproduction of this diagram is authorized.)

Chapter 6

OUTLINE OF SUGGESTED PROCEDURES FOR FORECASTING AIRCRAFT ICING

34. General:

a. The inherent capability of the present state of meteorological "art" to forecast aircraft icing must be considered as rudimentary because of the complexity and scale of variation of the phenomenon and the inadequate observational material routinely available. It would be feasible and desirable to develop a completely logical approach to the icing forecast from basic principles of physical and synoptic meteorology, but this presents a somewhat formidable task which has not yet been attempted. Whether it would result in an improved icing-forecast capability is not certain, but it would at least greatly facilitate the presentation of the subject to basic students and its understanding by those with meteorological knowledge but little or no aviation forecasting experience.

b. This chapter attempts to patch the various empirical data from icing research studies into the general forecast routine currently followed in most AWS detachments. It contains some hidden inconsistencies resulting from the limitations of the empirical data available. Only experience and intelligent experimentation by individual forecasters will make the most of the information presented here.

c. Even under these circumstances, aircraft-icing forecasting performance, as with any forecasting, will improve through following standard, logical, step-by-step procedures to insure that all known significant factors are considered during their preparation. To achieve this end, pertinent information present in the preceding chapters has been consolidated into a simple procedural outline in the next three paragraphs.

35. Phase I — Preliminary Determinations. The first phase of the procedure in the preparation of an aircraft-icing forecast consists of performing the following preliminary determinations. These are essential, regardless of the various methods selected in the succeeding phases:

a. **Clouds.** Determine the present and forecast the future distribution, type, and vertical extent of clouds along the flight path. Clouds can be analyzed and forecast using the information contained in surface weather observations, radiosonde observations, pilot reports, and surface and upper-air charts, using synoptic models, physical reasoning, and empirical studies. The influences of local effects such as terrain features, etc., should not be overlooked. AWSTR 231 discusses methods for middle-cloud forecasting. AWS TR 105-130 discusses cirrus cloud forecasting.

b. **Temperatures.** Determine those segments of the proposed flight path which will be in clouds colder than 0°C. A reasonable estimate of the freezing level can be made from the data contained in freezing-level charts, constant-pressure *charts, radiosonde*, reconnaissance, and AIREP observations, or by extrapolation from surface temperatures.

c. **Precipitation.** Check surface reports and synoptic charts for precipitation along the proposed flight path, and forecast the precipitation character and pattern during the flight — special consideration should be given to the possibility of freezing precipitation.

d. Centrally-Prepared Icing Forecasts. The Air Force Global Weather Central (AFGWC) issues manually produced, time phased icing forecasts for the Northern Hemisphere for the layer from 10,000 to 55,000 feet. These forecasts are for the following time periods: 7-12 hours, 12-24 hours, 24-36 hours, and 36-48 hours; and are transmitted via facsimile or teletype. Additionally, icing forecasts for 7-12 hours and 12-24 hours for the layer from the surface to 10,000 feet are produced for the contigu-

ous United States (CONUS) and Europe. These forecasts are based on computer printouts of temperature, dew point, and stability for over 400 rawinsonde observations, computer forecasts of synoptic scale systems and the forecast rules listed in this report. See AFGWCP 105-1 for a further discussion of these product.

36. Phase II — Basic Icing Forecast. The second phase of the procedure may be termed the preparation of the basic icing forecast. In this phase, the forecaster has a choice of three methods. The choice of the particular method to be used will be governed largely by data available to the forecaster, and by the amount of time which he has at his disposal to study the situation. Method 1 is the most sophisticated and will require the most time to use, especially if several prognostic soundings must be constructed. It is valid for icing in stratiform or cumuliform clouds, and yields quasi-objective forecasts of both the type and intensity of icing. Method 2 requires somewhat less time than Method 1, but is valid only for icing in stratiform clouds. Also, it does not by itself specify the intensity of icing. Method 3 consists of subjective interpretation of the type of data already available on a routine basis at most weather stations by means of a number of "forecasting rules," and normally does not require additional data plotting or analysis. Forecasters may wish to combine methods, for example, use Method 1 along certain critical portions of a given route, and Method 3 over the remainder.

NOTE: Each method and forecast rule assumes that two basic conditions must exist; viz., the surface of the aircraft must be colder than 0°C, and supercooled liquid-water droplets -- clouds or precipitation -- must be present in the flight path:

a. **Method 1.** Construct prognostic soundings or choose upwind soundings which are expected to be representative of conditions along the route at flight time. Check the degree of stability to be expected at flight altitude as indicated by the lapse rate. Then forecast the type and probable maximum intensity of icing in those cloud areas which have temperatures colder than freezing by means of the chart shown in figure 3, or a plastic overlay made from it. The details of this forecasting procedure were outlined in paragraph 30, but for the forecaster's convenience a concise summary of the instructions for the use of the chart has been printed directly on figure 3.

b. **Method 2.** This method, which is limited to stratiform clouds, may be resorted to if a lack of data or time, or some other reason, precludes the use of Method 1. Determine the probable phase condition of the cloud particles in stratiform clouds along the flight path using frost-point considerations (see paragraph 31d). The most practical procedure is to plot values of flight-altitude temperature and dew point from radiosonde data, reconnaissance data, pilot reports, or constant-pressure charts on figure 7, and read directly the likelihood of icing in stratiform clouds. This method by itself does not specify the intensity of the icing. Under these conditions, the probable (climatological) frequencies for trace, light, and moderate icing are 87%, 12%, and 1%, respectively. It can be seen that this method is identical with that part of Method 1 which is concerned with determining the likelihood of rime icing irrespective of intensity

c. **Method 3.** Again, if a lack of data or time, or some other reason, precludes the use of both Method 1 and Method 2, the empirical forecasting rules listed below can be used following a careful analysis of charts and reports already available on display in the weather station.

(1) *Icing Intensity Forecasts from Upper-Air Data.* Check upper-air charts, pilot or reconnaissance reports, and radiosonde reports for the dew-point spread at flight level, and check the upper-air charts for the type of temperature advection along the route.

Rule 1. If the temperature is (see paragraphs 22c, 31d, and figure 7):

a. 0°C to -7°C, and the dew-point spread is greater than 2°C, forecast *no* icing. There is an 80% probability of no icing under these conditions.

b. -8°C to -15°C, and the dew-point spread is greater than 3°C, forecast *no* icing -- 80% probability.

c. -16°C to -22°C, and the dew-point spread is greater than 4°C, forecast *no* icing — 90% probability.

d. Colder than -22°C, forecast *no* icing regardless of what the dew-point spread is — 90% probability.

Rule 2. If the dew-point spread is 2°C or less at temperatures 0°C to -7°C, or is 3°C or less at -8°C to -15°C, in (see paragraph 22b):

a. Zones of neutral or weak cold-air advection, forecast *trace* icing -- 75% probability.

b. Zones of strong cold-air advection, forecast *light* icing -- 80% probability.

c. Areas with vigorous cumulus build-ups due to insolational surface heating, forecast *light* icing -- 90% probability.

---

(2) *Icing-Intensity Forecasts from Surface-Chart Data.* If upper-air data and charts are not available, the conditions shown on the surface chart must be used as a guide for icing conditions, even though they are not as reliable as direct upper-air considerations. Check the surface charts for locations of the cloud shields of fronts, low-pressure centers, and precipitation areas along the route.

Rule 3. Within clouds *not* resulting from frontal activity or orographic lifting (see paragraph 23):

a. Over areas with steady non-freezing precipitation, forecast little or no icing.

b. Over areas without steady non-freezing precipitation, particularly in cumuliform clouds, forecast light icing.

Rule 4. Within clouds resulting from frontal activity or orographic lifting, neither the presence nor absence of precipitation can be used as indicators of icing (see paragraph 23).

Rule 5. Within clouds up to 300 miles ahead of the warm-front surface position, forecast light icing (see paragraph 20).

Rule 6. Within clouds, within 100 miles behind the cold-front surface position, forecast moderate icing (see paragraph 20).

Rule 7. Within clouds over a deep, almost vertical, low-pressure center, forecast moderate icing (see paragraph 20).

Rule 8. In freezing drizzle, below or in clouds, forecast moderate icing (see paragraph 20).

Rule 9. In freezing rain, below or in clouds, forecast severe icing (see paragraph 20).

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(3) *Icing-Type Forecasts.* Rules 1 through 9 forecast only the occurrence and intensity of icing, but not the type, The following rules apply to the type of icing.

Rule 10. Forecast *rime* icing when temperatures at flight altitude are colder than -15°C, or when between -1°C and -15°C in stable stratiform clouds (see paragraphs 18b and 19).

Rule 11. Forecast *clear* icing when temperatures are between 0°C and -8°C in cumuliform clouds and freezing precipitation (see paragraphs 18b and 19).

Rule 12. Forecast *mixed* rime-and-clear icing when temperatures are between -9°C and -15°C in unstable clouds (see paragraphs 18b and 19).

---

(4) *Forecasting from Extremely Limited Data.* Occasionally the forecaster is forced to make his forecast from very little, or even no current meteorological data. In these instances, icing forecasts can be based on the probabilities contained in figures 12 and 13, and table 7; then assuming ice will occur, the probable overall frequencies for trace, light, or moderate icing are 87%, 12%, and 1%, respectively (see paragraph 33).

37. Phase III — Modification of the Basic Icing Forecast. The final phase of the procedure is modification of the basic icing forecast that was obtained in Phase II. This is essentially a subjective process, and specific rules cannot be laid down. However, the forecaster should consider the following

items: Probable intensification or weakening of synoptic features, such as low-pressure centers, fronts, and squall lines during the time interval between the latest synoptic chart (data) and the forecast time; local influences, such as geographic location, terrain features, and proximity to ocean coastlines or lake shores; radar weather observations; pilot reports of icing; etc. But the forecaster should not on meteorological grounds alone intentionally overforecast or underforecast the amount (duration) and intensity of aircraft icing (see paragraph 3b). An overforecast of icing results in the aircraft's payload being decreased because of increased fuel load; while an underforecast of icing might result in an operational emergency. If necessary, refer to aircraft dash-one for additional guidance.

Chapter 7

AIRCRAFT ICING CLIMATOLOGICAL ESTIMATES

38. General. Aircraft icing climatological estimates may be required in addition to or in place of operational forecasts. Climatological estimates are used primarily for planning and design purposes, but can also be used in lieu of specific flight forecasts for areas of no data. Such an aircraft icing estimate is most accurate when based on past icing data for the specific route, month, and flight altitude concerned. If the icing observations required for such a study are not available, the analyst can estimate the probability of icing by determining the mean cloud cover for the desired route, month (or season), and altitude and multiplying by the mean percentage of time the clouds would be expected to be conducive to icing. This is feasible because studies have shown that the frequency of temperatures below 0°C appear to be statistically independent of the cloud-frequency distribution at the same level. Paragraph 33 and figure 12, this manual, show that the percentage of below-freezing clouds in which icing occurs is a function of temperature and altitude, ranging from an average near 40% at -2°C to below 10% near -30°C. These figures were obtained from AWS reconnaissance data. An assumption of 100% icing in all below-freezing clouds would generally result in a gross over-estimate of the climatological frequency. Along routes where current data are available, make a specific icing forecast using techniques in chapters 5 and 6 this manual. For planning, design, and for forecasts when current data are not available, use climatological estimates based on past aircraft icing reports.

39. A Technique for Producing a Climatological Icing-Frequency Estimate for a Given Route (Conventional Aircraft):

Step 1. Determine the percent frequency of 6/10 to 10/10 cloud cover along the flight level for the specified season using AWS Technical Report 167[4]. For climatological purposes an average value for the overall route is suggested, although it may be desirable to divide long routes into segments.

Step 2. Determine the average temperature and standard deviation along the route (or segment) and flight level for the specified season. British Met. Office, Geophysical Memoir #101, "Upper Air Temperatures Over the World", is a recommended source (available at Technical Services offices, AWS wings).

Step 3. Obtain the estimate of the percent of clouds with icing for the average temperature and standard deviation by using figure 14 for the 700-mb level and figure 15 for the 500-mb level.

Step 4. Multiply the cloud frequency value obtained in Step 1 by the value obtained in Step 3. The result provides a climatological estimate of the probability of icing along the route or segment during the specified season. This percent value can be converted to "flight time" or to "number of miles" of the flight route. When you provide this information to your operator emphasize you are providing seasonal values and climatological values (icing encountered on individual flights can vary markedly from these values).

40. Additional Considerations and Limitations:

a. Although icing frequencies for 4/10 and 5/10 cloud cover can be calculated using AWSTR 167, the 6/10 to 10/10 statistics would be most meaningful to planners and operators.

b. Although icing can occur at temperatures warmer than -2°C and colder than -36°C, the frequency of occurrence is extremely low (approaching 0%). As previously

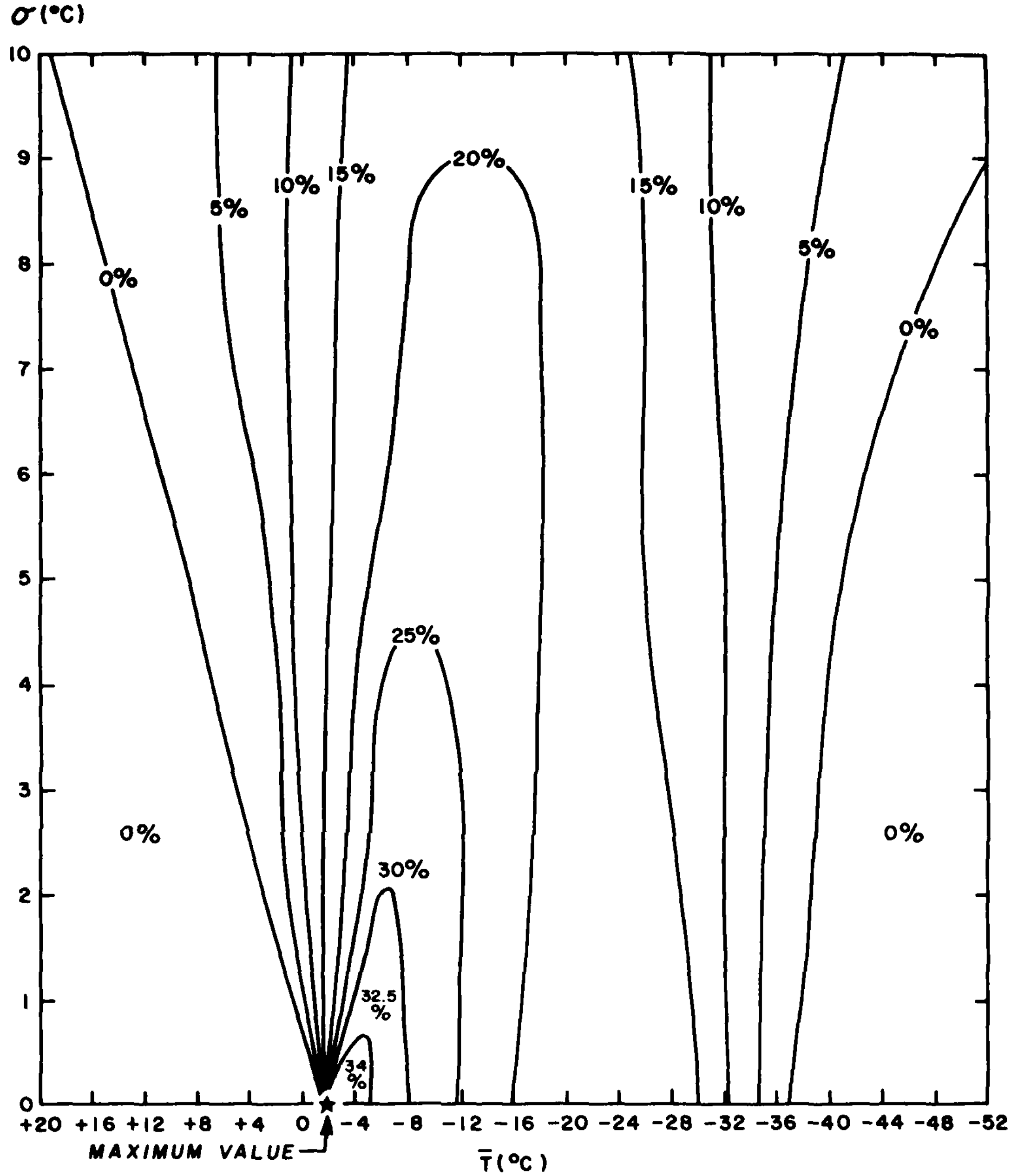

Figure 14—Percent Frequency of Icing in Clouds at 700 mb for Given Mean Temperature and Standard Deviation.

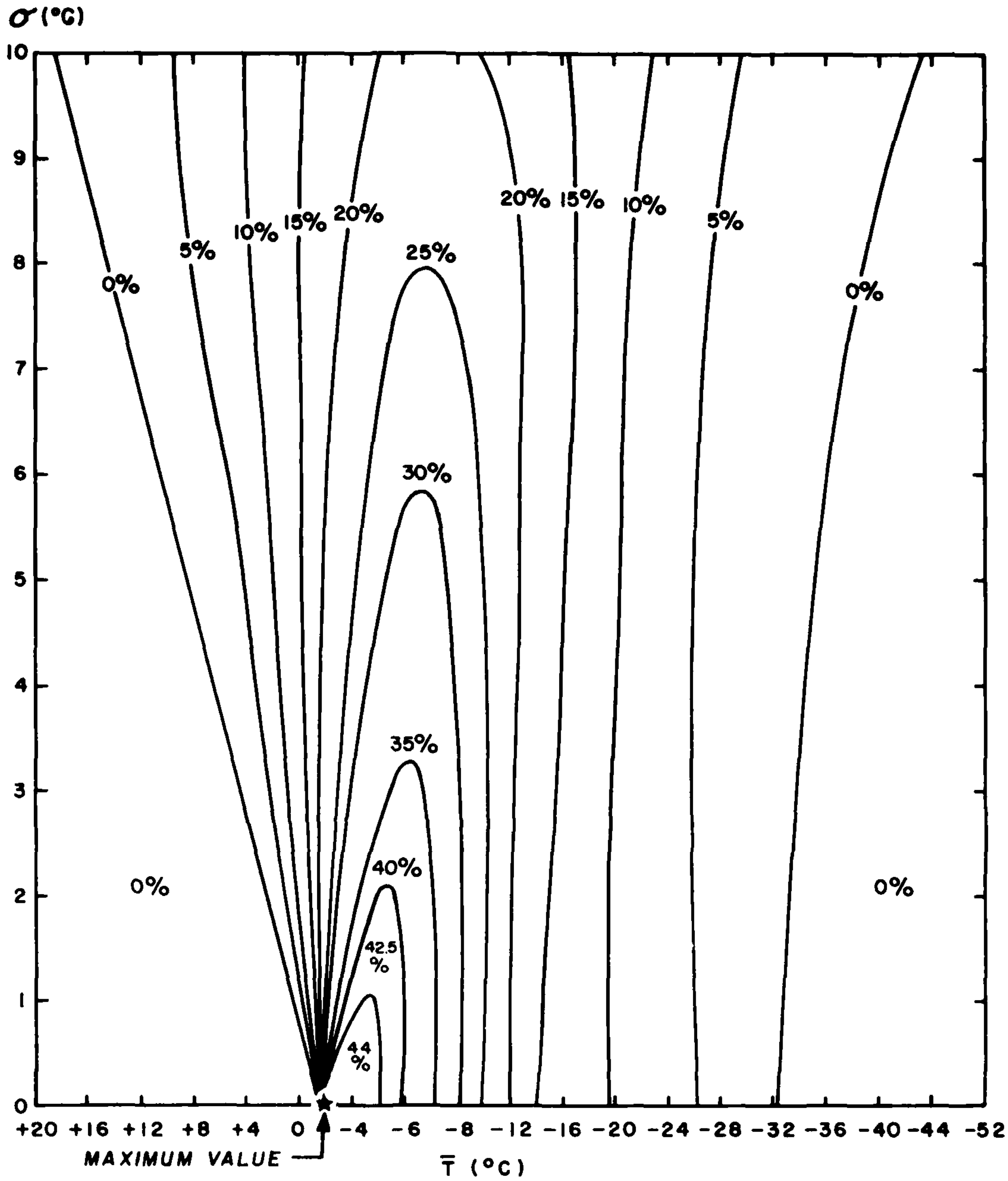

Figure 15—Percent Frequency of Icing in Clouds at 500 mb for Given Mean Temperature and Standard Deviation.

mentioned, aerodynamic heating (at the warm end of the icing spectrum) and the collection efficiency of conventional aircraft are only two of a number of factors which tend to restrict icing to the designated spectrum (basically -2°C through -36°C; see figure 12).

c. These calculations are based on data relative to conventional (reciprocating engine) aircraft. They may differ for jet aircraft operation, due to dynamic heating, different collection efficiency, etc; however, jet aircraft seldom operate for extended distances or times at the levels where icing predominates. If you encounter such a case, we recommend special treatment of the problem and that you consult your climatologist and technical services representatives.

d. No attempt is made to distinguish between types of icing.

e. Consideration is given to the standard deviation of temperature to reduce the over-estimation or under-estimation of icing frequency when the average temperature is near either end of the temperature-dependent icing spectrum.

f. Should the proposed flight level be between the 700 and 500-mb surfaces, interpolation between the values obtained on Figures 14 and 15 is suggested.

g. Charts of climatological probabilities of icing over the Northern Hemisphere are given in AWSTR 220 [52].

41. An Example Illustrating Use of the Technique — Problem. To compute probability of icing at 10,000 feet over Scott AFB in January:

a. Use AWSTR 107 to determine the percent frequency of 6/10 to 10/10 cloud cover for the desired point and month. Figure 4 shows a value of 15 percent at 5,000 to 10,000 feet and figure 6 shows a value of 12 percent at 10,000 to 15,000 feet. Averaging the two figures gives a cloud frequency of 13.5 percent at 10,000 feet.

b. Use Geophysical Memoir No. 101 (Brit. Met. Off.) to obtain the average temperature ($\bar{T}$) and its standard deviation (σ) for the desired point and month. Plate 1 therein shows an average temperature of -6°C, and Plate 45 shows a σ value of 5°C.

c. Use figure 14 to obtain the percent frequency of icing in clouds at 700 mb. Entering figure 14 with $\bar{T}$ and σ values of -6°C and 5°C, respectively, we find that 22 percent of the clouds result in icing.

d. Multiply the cloud frequency (13.5%) by the frequency of icing in clouds (22%) to obtain the climatological probability (3%) of an aircraft encountering icing at 10,000 feet over Scott AFB in January.

STUDY OF DEW-POINT SPREAD AND TEMPERATURE AS FACTORS IN AIRCRAFT ICING

Certain data collected on routine AWS weather-reconnaissance flights over the North Atlantic and North Pacific Oceans during the period May 1952 through June 1954, and over the Arctic Ocean during May 1952 through June 1955, were studied at Headquarters AWS. They consisted of more than 12,000 observations made at 700 mb (9,900-foot pressure altitude) and 500 mb (18,300-foot pressure altitude) when the air temperature was reported to be +2°C or colder at flight level, and when the aircraft was flying in clouds at least 25% of the time, i.e., flight-condition code figures 6, 7, 8, or 9. These data are a small portion of those for the same period and area analyzed by Perkins, Lewis, and Mulholland [37].

For the phase of the study reported here[3], only those observations made when the aircraft was flying in stratiform clouds at free-air temperatures between 0°C and -32°C and which included a reported dew point (there were 5,463 such reports) were analyzed to determine the relationships between temperature, dew-point spread, and icing occurrence. Consolidated results of the analysis are shown in tables 8 and 9, and in figure 16.

Table 8 shows that the predominant temperature range for aircraft icing under these flight conditions was from -3°C to -7°C. As the temperature becomes colder, the percentage of icing generally decreases. The comparatively small percentage of icing cases in the range 0°C to -2°C can be explained either by aerodynamic heating of the aircraft components or by errors associated with measuring temperatures near freezing or by both.

Table 9 shows that the predominant dew-point spread, irrespective of temperature, for aircraft icing under these flight conditions was 0°C, with the minimum at spreads of 7°C or more. Although a general decrease in icing frequency, percentage-wise, from 0° spread to a spread of 7°C or more would be expected, there was a secondary maximum at a spread of 4°C, and a secondary minimum at a spread of 2°C. These double maxima and minima may be real, or may be irregularities due to the comparatively small number of cases at the larger spreads. Although icing intensities are not shown in Table 9, it was noted during the analysis that 94% of the cases of moderate icing (equivalent to light in new terminology) occurred with a reported dew-point spread $\leqslant$ 2°C, and that all cases of severe icing (equivalent to moderate in new terminology) occurred with a zero dew-point spread.

These results agree well with the empirical conclusions of Appleman [5] , and with the findings of WADC [44] during their all-weather flight testing. From frost-point theory, Appleman showed that icing in stratiform clouds should occur only when the dew point (with respect to water) satisfies the inequality.

$$\star \qquad T_f \geqslant T \geqslant T_d \qquad (1)$$

where T = air temperature, T_d = dew point and T_f = frost point. Using the relation $T_f \approx 0.9T_d$ equation (1) can be rewritten as:

$$T_f = 0.9T_d \geqslant T \qquad (2)$$

However, to compensate for inaccuracies in radiosonde humidity measurements at subfreezing temperatures, he found empirically that inequality (2) should be modified to the form

$$0.8\ T_d \geqslant T \qquad (3)$$

or in terms of dew-point spread as

$$T - T_d \leqslant -0.2\ T_d \qquad (4)$$

Note that above equations are for zero and negative values.

[3]Other phases of the study included analyses of the data for icing frequencies in various temperature ranges according to: flight conditions (cloud amount), cloud type, and latitude zone. Frequencies were tabulated for each of the several types and intensities of icing.★

TABLE 8

Frequency of Aircraft Icing by Air Temperature and Dew-Point Spread
(from observations having a dew-point report
made in stratiform clouds)

Air Temperature (°C)		Number of Observations	Number of Icing Cases	Percent Frequency of Icing
0 to -2	With spread = 0°	245	41	16.7
	With spread > 0°	49	8	16.3
	Total	294	49	16.7
-3 to -7	With spread ≤ 1°	1101	563	51.1
	With spread > 1°	114	37	32.5
	Total	1215	600	49.4
-8 to -12	With spread ≤ 2°	1018	418	41.1
	With spread > 2°	141	32	22.7
	Total	1159	450	38.8
-13 to -17	With spread ≤ 3°	1251	237	18.9
	With spread > 3°	133	15	11.3
	Total	1384	252	18.2
-18 to -22	With spread ≤ 4°	772	134	17.4
	With spread > 4°	77	7	9.1
	Total	849	141	16.6
-23 to -27	With spread ≤ 5°	347	38	11.0
	With spread > 5°	35	5	14.3
	Total	382	43	11.3
-28 to -32	With spread ≤ 6°	160	15	9.4
	With spread > 6°	20	0	0.0
	Total	180	15	8.3
Grand Total		5463	1550	28.4

Appleman concluded that when temperature is plotted against dew point on a graph such as figure 7, those observations of fog or cloud lying between the lines $T = T_d$ and $T = 0.8T_d$ represented cases of supercooled liquid-water clouds, and that in these cases icing was highly probable. He verified this conclusion with only a relatively small sample (49 cases) of weather-reconnaissance observations.

★ In the present study, Appleman's conclusion was verified with a considerably larger sample of reconnaissance data (5,463 observations in sub-freezing stratiform clouds). The results are presented in Figure 16, on a graph whose coordinates are temperature and dew-point spread. On this graph, the horizontal temperature axis (x-axis) is the zero degree dew point spread, and the line $(T - T_d) = -0.2T_d$, which is equivalent form of $T = 0.8T_d$, is the heavy line running diagonally upward to the right from the origin (termed the "Appleman line").

Percent frequencies cumulative with increasing spread are shown for each of the temperature ranges. Nearly all of the icing cases fall in the area between the x-axis and the Appleman line. The exceptions noted when the temperature is between 0°C and -5°C can be explained by either aerodynamic heating of the aircraft components or errors in temperature and moisture measurements, or both. The large "hump" in the cumulative frequency

TABLE 9

Frequency of Aircraft Icing by Dew-Point Spread Only (from observations having a dew-point report made in stratiform clouds at temperatures between 0°C and -32°C)

Dew-Point Spread (°C)	Number of Observations	Number of Icing Cases	Percent Frequency of Icing
0	3565	1243	34.9
1	719	143	19.9
2	416	54	13.0
3	235	33	14.0
4	140	24	17.1
5	87	14	16.1
6	86	12	14.0
≥ 7	215	27	12.5
Grand Total	5463	1550	28.4

isopleths in the temperature range -23°C to -27°C (shown as the dashed portion of the curves) is due to three reports of icing at reported dew-point spreads of 7°C (out of a total of 43 icing reports in that temperature range). These could very possibly be spurious reports due to faulty humidity measurements, or to errors in recording and/or transcribing these data. The rapid convergence of the cumulative frequency isopleths at temperatures colder than -25°C is due primarily to the general decrease in icing frequency (see table 8), and also to the marked decrease in the number of dew-point reports at these temperatures.

Although these data used in this attachment were taken from observations in stratiform clouds only, considerations of overall icing frequencies as a function of temperature indicate that the results presented may be used at least as a guide to forecasting icing-occurrence probabilities in any type of clouds, as suggested in paragraph 31d(2), this report.

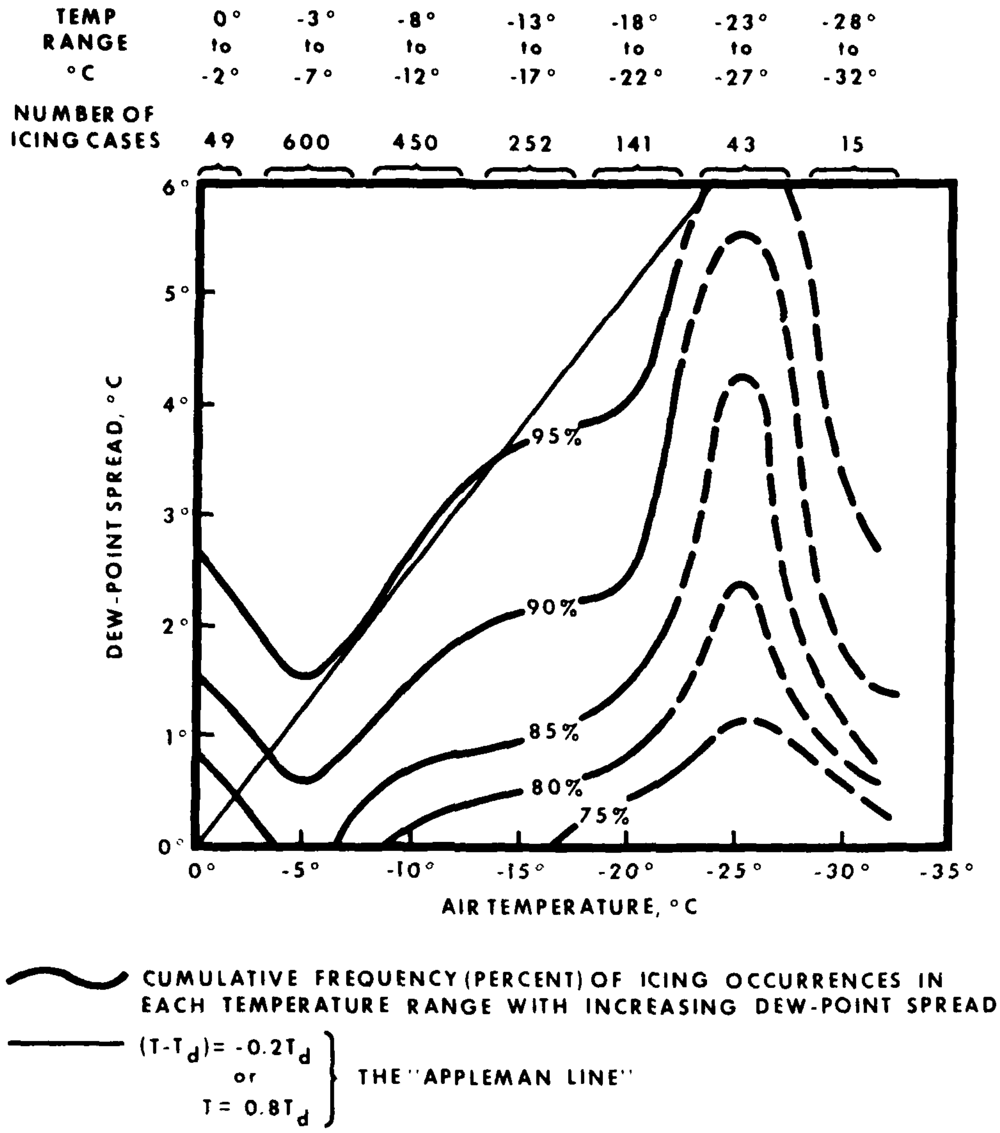

Figure 16—Graph of Cumulative Frequencies of Icing Occurrences as Functions of Temperature and Dew-Point Spread.

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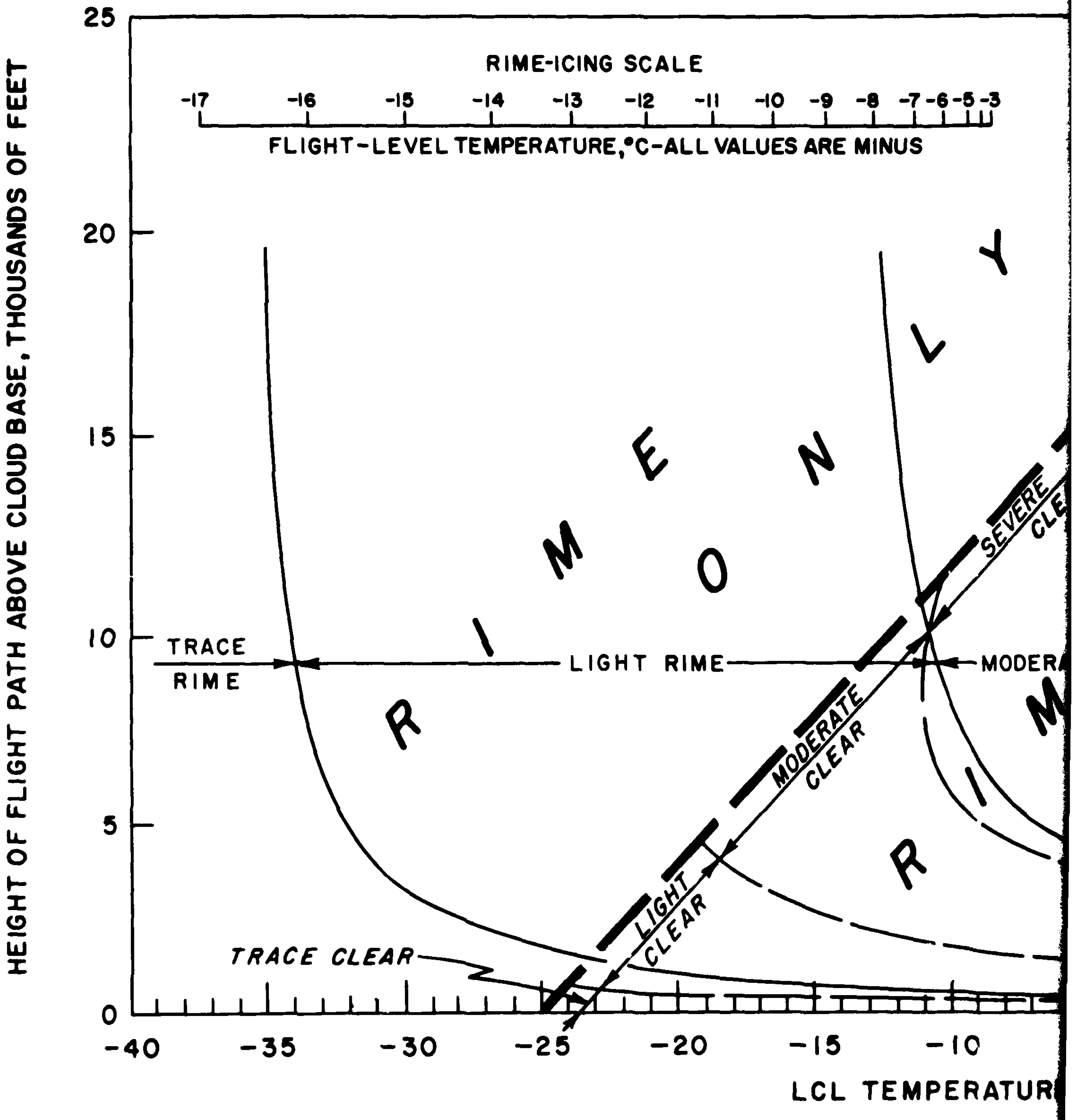
AIRFRAME ICING REPORTING TABLE

Intensity	Ice Accumulation	Pilot Report
Trace	Ice becomes perceptible. Rate of accumulation slightly greater than rate of sublimation. It is not hazardous even though deicing/anti-icing equipment is not utilized, unless encountered for an extended period of time—over one hour.	A/C Ident., Location, Time, (GMT) Intensity of Type*, Altitude/FL, Aircraft Type, IAS
Light	The rate of accumulation may create a problem if flight is prolonged in this environment (over one hour). Occasional use of deicing/anti-icing equipment removes/prevents accumulation. It does not present a problem if the deicing/anti-icing equipment is used.	Example:
Moderate	The rate of accumulation is such that even short encounters become potentially hazardous and use of deicing/anti-icing equipment or diversion is necessary.	Holding at Westminster VOR, 1232Z Light Rime Icing, altitude six thousand, Jetstar IAS 200 kts
Severe	The rate of accumulation is such that deicing/anti-icing equipment fails to reduce or control the hazard. Immediate diversion is necessary.	

* Rime Ice: Rough, milky. opaque ice formed by the instantaneous freezing of small supercooled water droplets.

Clear Ice: A glossy, clear or translucent ice formed by the relatively slow freezing of large supercooled water droplets.



RIME-ICING SCALE
-17
-16
-15
-14
-13
-12
-11
-10
-9
-8
-7
-6
-5
-3
FLIGHT-LEVEL TEMPERATURE,°C-ALL VALUES ARE MINUS
HEIGHT OF FLIGHT PATH ABOVE CLOUD BASE, THOUSANDS OF FEET
25
20
15
10
5
0
RIME ONLY
TRACE RIME
LIGHT RIME
MODERA
SEVERE
CLE
MODERATE CLEAR
LIGHT CLEAR
TRACE CLEAR
RIM
-40
-35
-30
-25
-20
-15
-10
LCL TEMPERATUR

Figure 3a.

INSTRUCTIONS

1. CHOOSE REPRESENTATIVE SOUNDING.
2. DETERMINE PROBABLE ICING TYPE AT FLIGHT LEVEL
   A. IF SOUNDING IS CONDITIONALLY UNSTABLE ($\gamma_{DRY} > \gamma > \gamma_{SAT}$), CLEAR ICING MOST PROBABLE. UPPER LIMIT OF CLEAR ICE IS −25°C.
   B. IF SOUNDING IS STABLE ($\gamma < \gamma_{SAT}$), RIME ICING MOST PROBABLE. USE RIME-ICING SCALE TO DETERMINE UPPER LIMIT OF RIME ICE. PLACE RIME-ICING SCALE AT FLIGHT LEVEL, PARALLEL TO ISOBARS WITH TEMPERATURE MARK ON SCALE COINCIDING WITH TEMPERATURE OF SOUNDING. IF DEWPOINT OF CURVE IS TO LEFT OF T-1 MARK, FORECAST NO RIME ICE; IF DEWPOINT CURVE TO RIGHT OF T-1 MARK, FORECAST RIME ICE.
3. IF ICING IS FORECAST AT FLIGHT LEVEL, LOCATE LCL OR CLOUD-BASE LEVEL
   A. IF NO FRONTAL INVERSION ON SOUNDING, DRAW VERTICAL LINE UPWARD THROUGH THE LCL OR CLOUD-BASE LEVEL TEMPERATURE ON SOUNDING TO FLIGHT LEVEL.
   B. IF FRONTAL INVERSION INDICATED ON SOUNDING, DO NOT DRAW VERTICAL LINE.
4. PLACE LCL TEMPERATURE SCALE PARALLEL TO ISOBARS AT LCL WITH 0 ON SCALE COINCIDING WITH 0°C ISOTHERM.
5. READ ICING INTENSITY AT INTERSECTION OF FLIGHT LEVEL AND VERTICAL LINE, OR FLIGHT LEVEL AND SOUNDING IF THERE IS A FRONTAL INVERSION, USING SOLID-LINE CURVES FOR RIME ICE AND DASHED-LINE CURVES FOR CLEAR ICE. (SEE PARA 27, AWSM 105-39 FOR DETAILS).

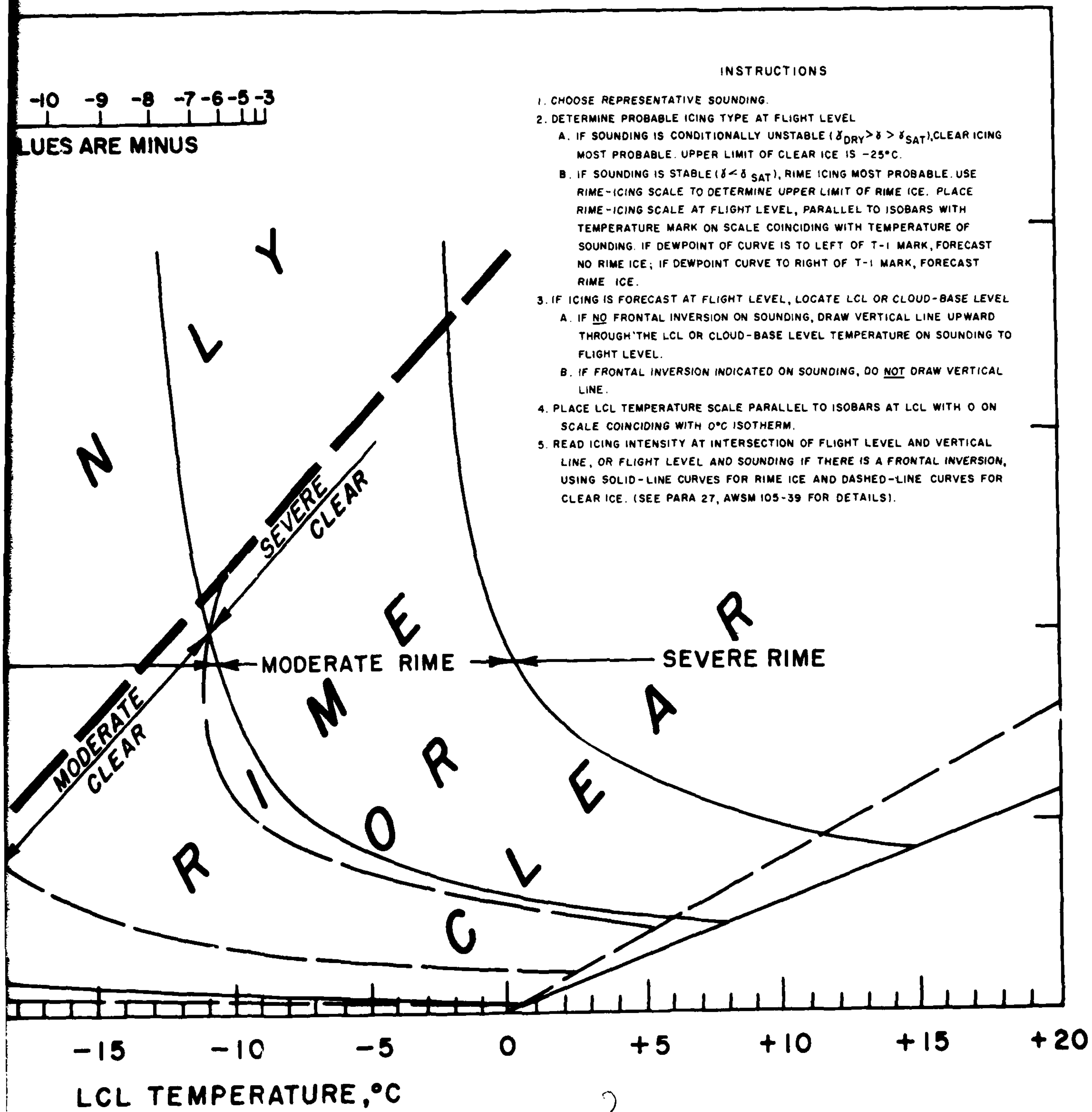


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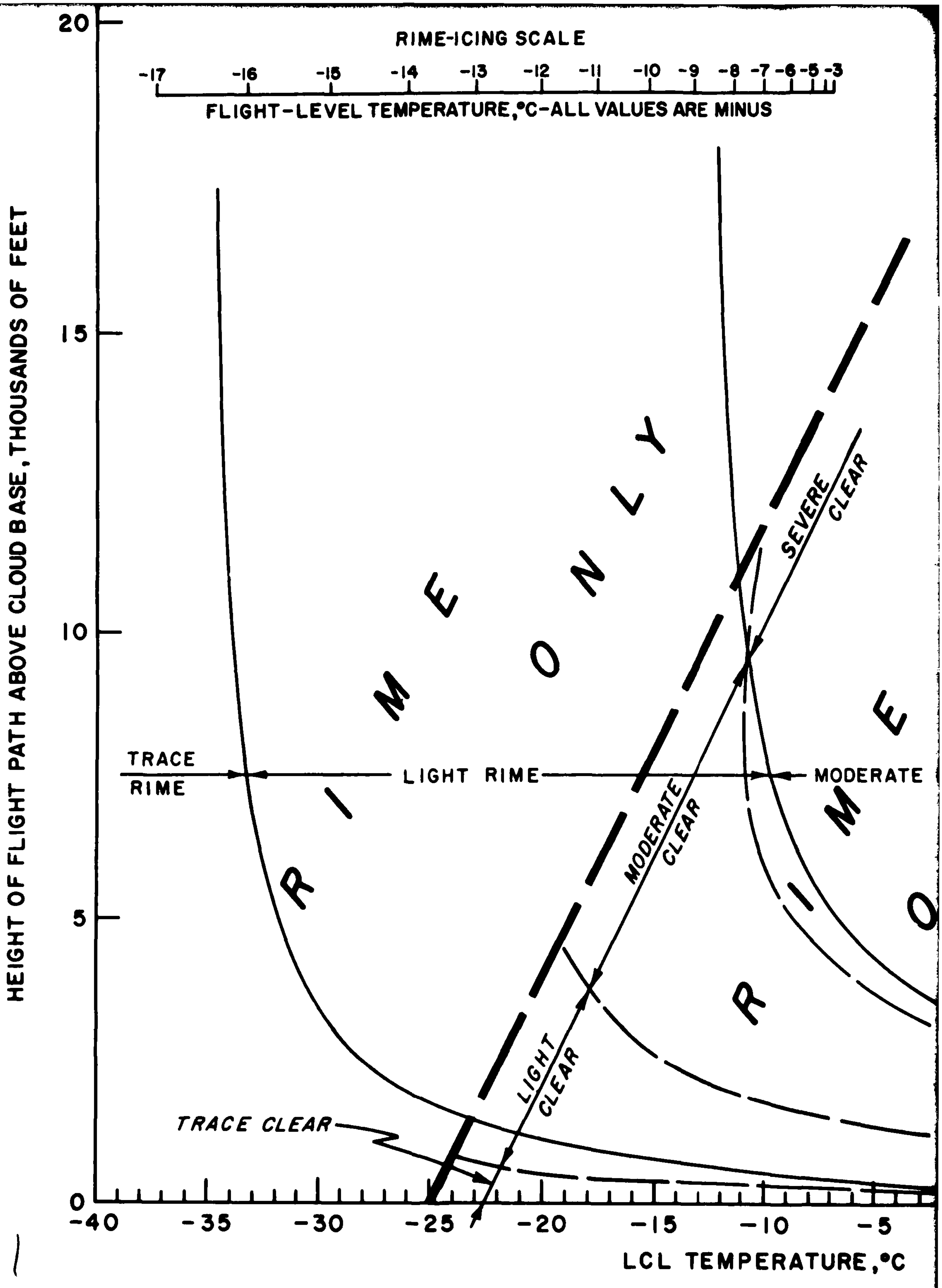
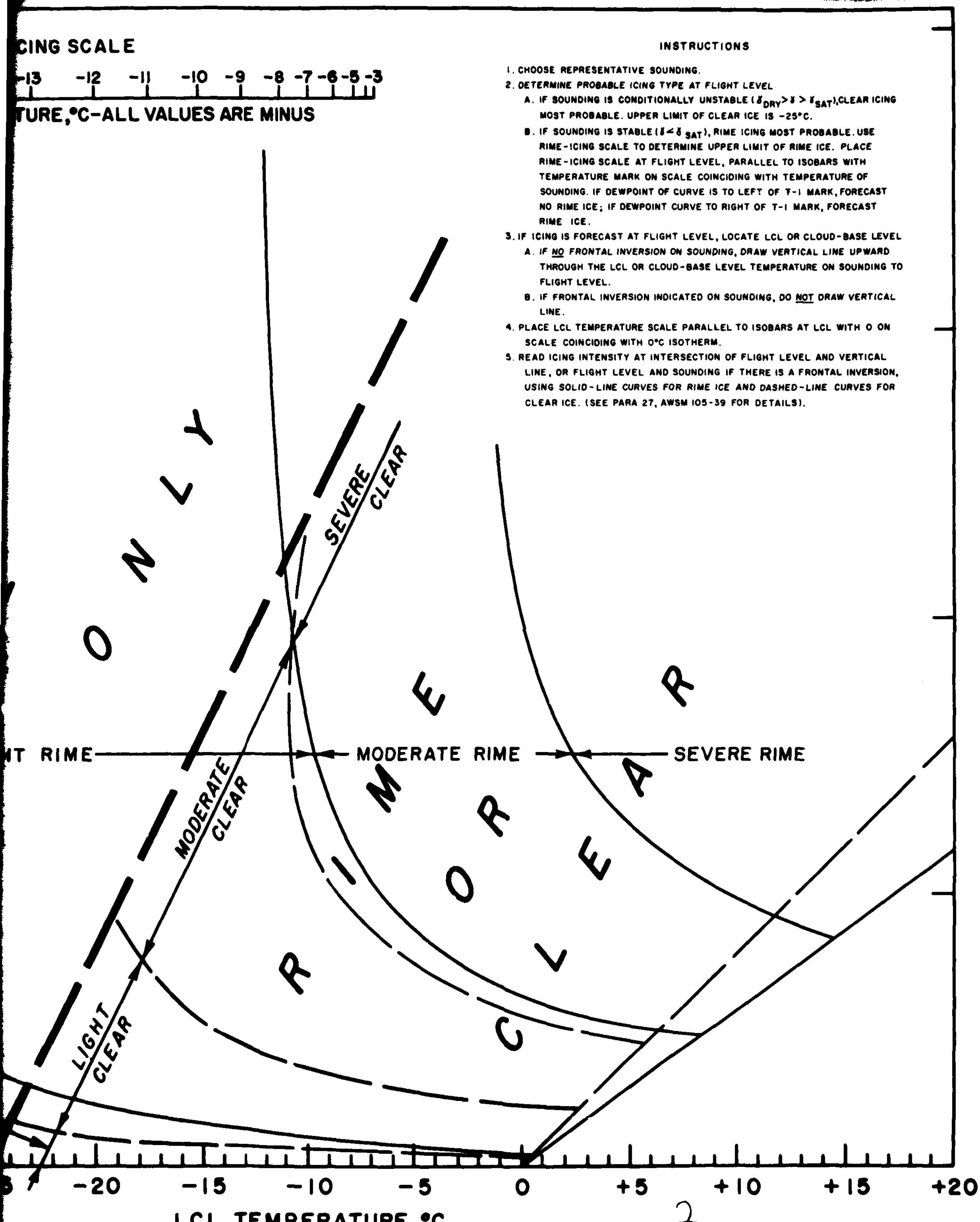
Figure 3a.



RIME-ICING SCALE
-17 -16 -15 -14 -13 -12 -11 -10 -9 -8 -7 -6 -5 -3
FLIGHT-LEVEL TEMPERATURE, °C-ALL VALUES ARE MINUS
HEIGHT OF FLIGHT PATH ABOVE CLOUD BASE, THOUSANDS OF FEET
20
15
10
5
0
RIME ONLY
RIME
TRACE RIME
LIGHT RIME
MODERATE
SEVERE CLEAR
MODERATE CLEAR
LIGHT CLEAR
TRACE CLEAR
-40 -35 -30 -25 -20 -15 -10 -5
LCL TEMPERATURE, °C

Figure 3b.



INSTRUCTIONS

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3. IF ICING IS FORECAST AT FLIGHT LEVEL, LOCATE LCL OR CLOUD-BASE LEVEL
   A. IF NO FRONTAL INVERSION ON SOUNDING, DRAW VERTICAL LINE UPWARD THROUGH THE LCL OR CLOUD-BASE LEVEL TEMPERATURE ON SOUNDING TO FLIGHT LEVEL.
   B. IF FRONTAL INVERSION INDICATED ON SOUNDING, DO NOT DRAW VERTICAL LINE.
4. PLACE LCL TEMPERATURE SCALE PARALLEL TO ISOBARS AT LCL WITH 0 ON SCALE COINCIDING WITH 0°C ISOTHERM.
5. READ ICING INTENSITY AT INTERSECTION OF FLIGHT LEVEL AND VERTICAL LINE, OR FLIGHT LEVEL AND SOUNDING IF THERE IS A FRONTAL INVERSION, USING SOLID-LINE CURVES FOR RIME ICE AND DASHED-LINE CURVES FOR CLEAR ICE. (SEE PARA 27, AWSM 105-39 FOR DETAILS).

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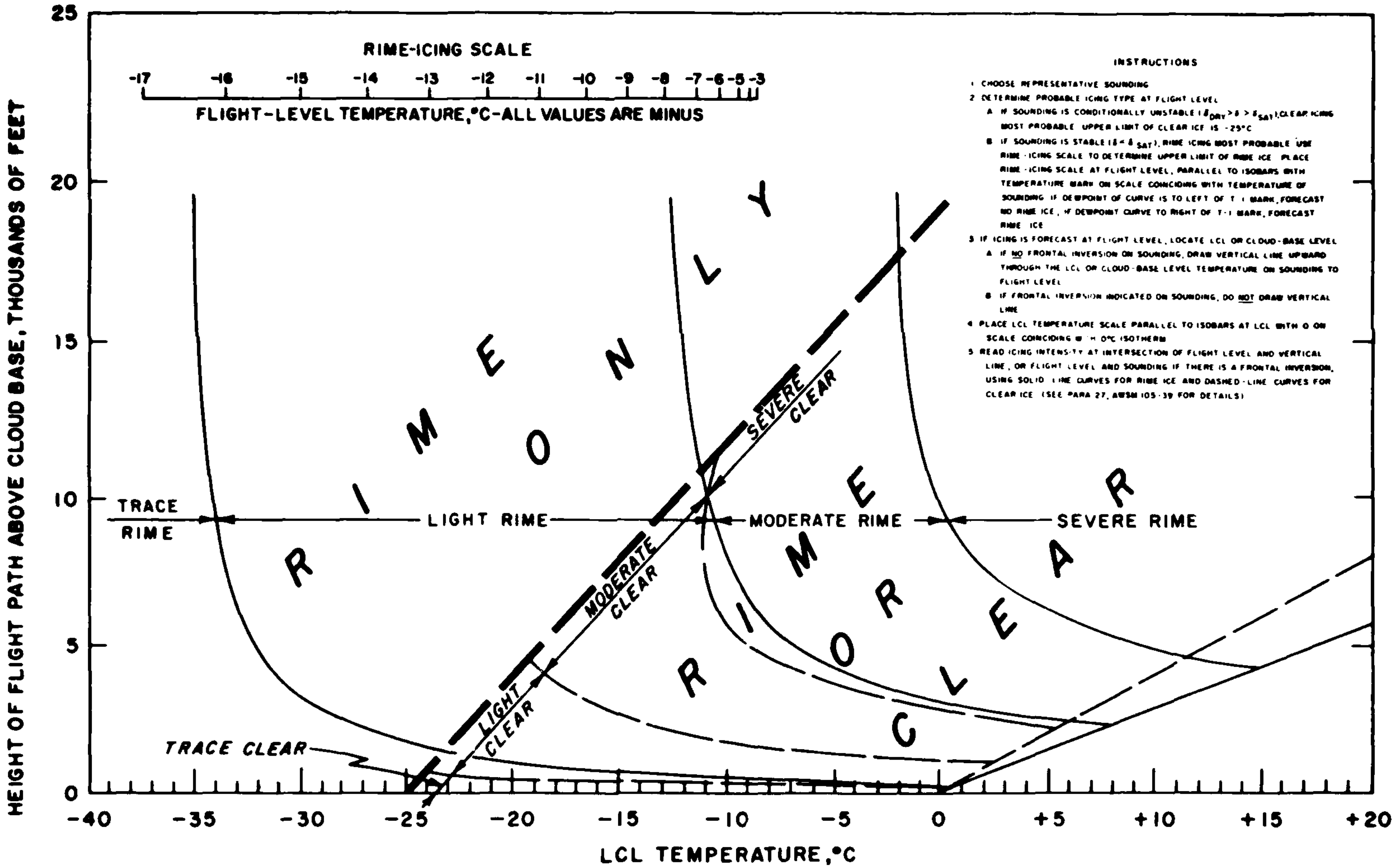

Figure 3c. A full-scale overlay for use with the Skew-T, Log P Diagram, DOD WPC 9-16-1, to determine the most probable icing intensity in cumuliform and stratiform clouds. (Local reproduction authorized.)

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